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BOLTED JOINTS IN COMPOSITE STRUCTURES: DESIGN, ANALYSIS AND VERIFICATION

TASK II TEST RESULTS -- MULTIFASTENER JOINTS

20090521 017

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This technical report has been reviewed and is approved for publication.

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This report presents results from an experimental task that studied the effects of many parameters on composite-to-metal multifastener joints. The addressed parameters included: laminate layup, fastener arrangement, adjacent cut-out, load type, load eccentricity (single versus double shear), fastener head geometry, and test environment. Test laminates were fabricated using uindirectional AS1/3501-6 graphite/epoxy material, and transferred the applied load to aluminum plates. Test results were obtained on many fastener arrangements, including some with a neighboring circular cut-out. Many failure modes were observed and recorded. In some test cases, despite the close tolerances in the specimen/hole/fastener geometries, different predominant failure modes were observed in the replicates. A unique fastener load measurement technique, using strain-gaged bolts, was applied to every test case to compute the fractional fastener loads corresponding to the various test conditions. This information, in conjunction with photographic records of failed test specimens, will be very useful in validating the strength of multifastener joints being developed in this ongoing Northrop/AFWAL program.

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Bolted Joints in Composite Structures: Design, Analysis and Verification
Task II Test Results--Multifastener Joints.

AD-B099065

PREFACE

This report was prepared under Contract F33615-82-C-3217, titled "Bolted Joints in Composite Structures: Design, Analysis and Verification," and administered by the Air Force Wright Aeronautical Laboratories. The Air Force project engineer for the program is Dr. V. B. Venkayya. Capt. M. Sobota and 2nd Lt. D. L. Graves are the program co-monitors at the Air Force. The program manager and the principal investigator at Northrop is Dr. R. L. Ramkumar.

This report provides details of the experimental part of Task 2 in the referenced progam (Project 2401).

The successful completion of this reported task was made possible by the efforts of the following personnel:

Specimen Fabrication	A. Hall, C. Williams
Testing	P. Dagger, M. Steele, B. Mays, A. McQuillian
Graphics	R. Cordero
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SECTION 1

INTRODUCTION

Bolted joints are a prime means of load transfer in aircraft components. Compared to other joining techniques such as bonding and welding, they are reliable and structurally efficient, as well as cost effective. However, bolted joint locations give rise to stress concentrations and could be the source of static and fatigue structural failures.

No analytical method has yet been developed to a stage where it can be used as an efficient design tool to predict the strength and life of a bolted plate, especially if it is a laminate. Presently employed design procedures for bolted laminates are generally extrapolations of the procedures used for bolted metallic plates, and are based on extensive testing, empirical data and finite element analyses. Existing analyses do not account for the inherent three-dimensionality of the problem which is made complex by the anisotropy and inherent heterogeneity of the material, its susceptibility to various failure modes (delaminations and intra-ply failures), load eccentricity, bolt flexibility and the joint geometry (bolted plate dimensions, fastener size and arrangement, etc.).

The ongoing Northrop/AFWAL program (Reference 1-1) was initiated with the following objectives: (a) to develop analytical methods for strength and life prediction of bolted joints, accounting for stress concentration interactions, if any; (b) to verify the developed analyses through a series of experiments; and (c) to develop a comprehensive, design-oriented guide for bolted joints in composite structures.

To achieve the above objectives, the program was divided into four major tasks:

(1) Task I -- Analytical Techniques for Single Fastener Joints

Under this task, analytical techniques were developed for the prediction of the strength and durability of single fastener joints, accounting for finite joint geometry effects and localized through-the-thickness strain variation. The developed analyses were verified by testing 450 single-fastener specimens of various configurations (see References 1-2 and 1-3).

(2) Task II -- Analytical Techniques for Multiple Fastener Joints/Stress Concentration Interactions

Under this task, analytical techniques are being developed for the prediction of the strength and lifetime of multiple fastener joints, accounting for stress concentration interaction effects, if any. The developed analyses will be verified by conducting over 160 static tests on multifastener specimens with different fastener arrangements, and in selected cases, with circular cutouts adjacent to the fasteners.

(3) Task III -- Full Scale Verification

To ensure that the methodology developed under Tasks I and II can be used to design and analyze full-scale bolted structures, tests were conducted on elements representative of a typical bolted vertical stabilizer root section. These test elements will be analyzed using the methodology developed in Tasks I and II, and theoretical predictions will be correlated with experimental results.

(4) Task IV -- Design Guide Development

Analyses developed in the above tasks, along with generated test results, will be used to develop a guide for the design of bolted composite structures. The guide will include easy-to-use design curves and detailed instructions, with examples, for the use of these curves and the developed computer programs.

At this stage of the program, all the tests have been completed, Task I analyses have been developed and validated, and the analysis developed under Task II is being verified. This report presents results from the completed multifastener (Task II) tests.

SECTION 2

DETAILS OF THE EXPERIMENTAL PROGRAM

2.1 Overview of Task II Tests on Multifastener Joints in Composites

Over 160 static tests were conducted on composite-to-metal multifastener joints, in single and double shear load transfer configurations (see Figures 2-1 and 2-2). Fastener arrangements ranged in complexity from two in tandem to eight fasteners with an adjacent cut-out. Table 2-1 lists the various Task II tests.

2.2 Test Laminates

Bolted laminates were fabricated using AS1/3501-6 graphite/epoxy unidirectional prepreg material containing approximately 35% resin by weight. Laminates were fabricated using the processing procedure described in Reference 1-2. Fabricated panel quality was assessed via ultrasonic inspection, and laminate layup was verified by examining its cross-sections under a microscope. The nominal cured ply thickness in the test laminates was 0.0052 inch.

Tested laminates include 20 and 40-ply laminates with 50/40/10, 70/20/10, 30/60/10 and 25/60/15 (percentages of 0^o, $\pm45^o$ and 90^oplies, respectively) layups. The 20-ply 50/40/10, 70/20/10 and 30/60/10 layups have $[(45/0/-45/0)_2/0/90]_s$, $[45/0/-45/0_3/90/0_3]_s$ and $[45/0/-45/0/45/90/-45/0/\pm45]_s$ stacking sequences, respectively. The 40-ply 50/40/10 and 70/20/10 layups have $[(45/0/-45/0)_2/0/90]_{2s}$ and $[45/0/-45/0_3/90/0_3]_{2s}$ stacking sequences, respectively. The 40-ply 25/60/15 laminate has a $[45/0/-45/0/45/90/-45/0/\pm45]_{2s}$ stacking sequence, with the twelfth 0^o ply replaced by a 90^o ply. If the twelfth ply had been a 0^o ply, the originally intended 30/60/10 layup would have resulted.

2.3 Fastener Arrangements

The fastener arrangements considered in this test program include: two fasteners in tandem, two at an angle to the load direction, three fasteners in two arrangements, four fasteners in a rectangular pattern, five fasteners in tandem, three fasteners in each of two rows with an adjacent cut-out, and four fasteners in each of two rows with a cut-out either between or adjacent to the rows. A row of fasteners is perpendicular to the load direction. The fastener spacing in the load and transverse directions (S_L and S_T, respectively),

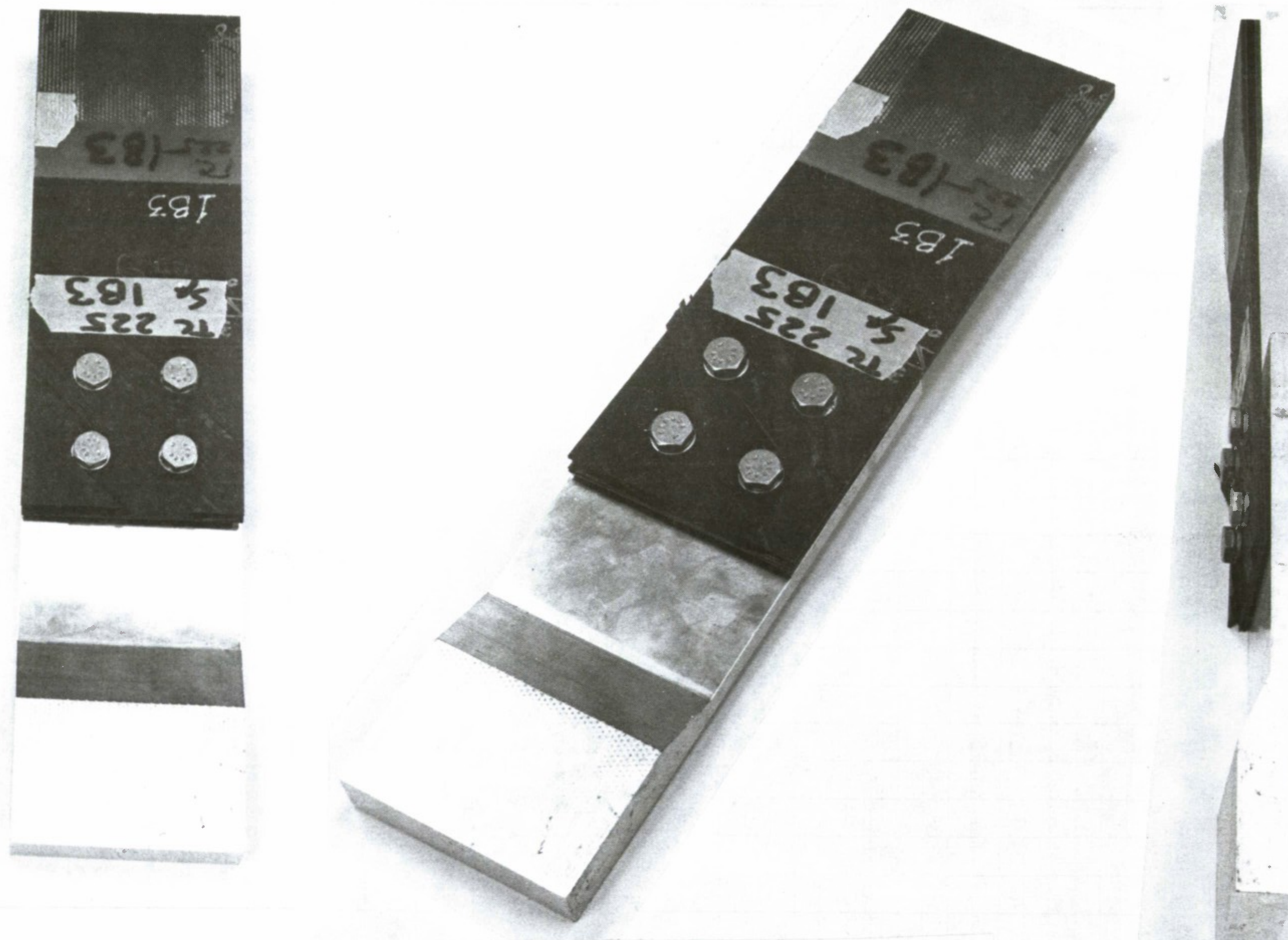


Figure 2-1. Sample Photographs of A Single Shear Test

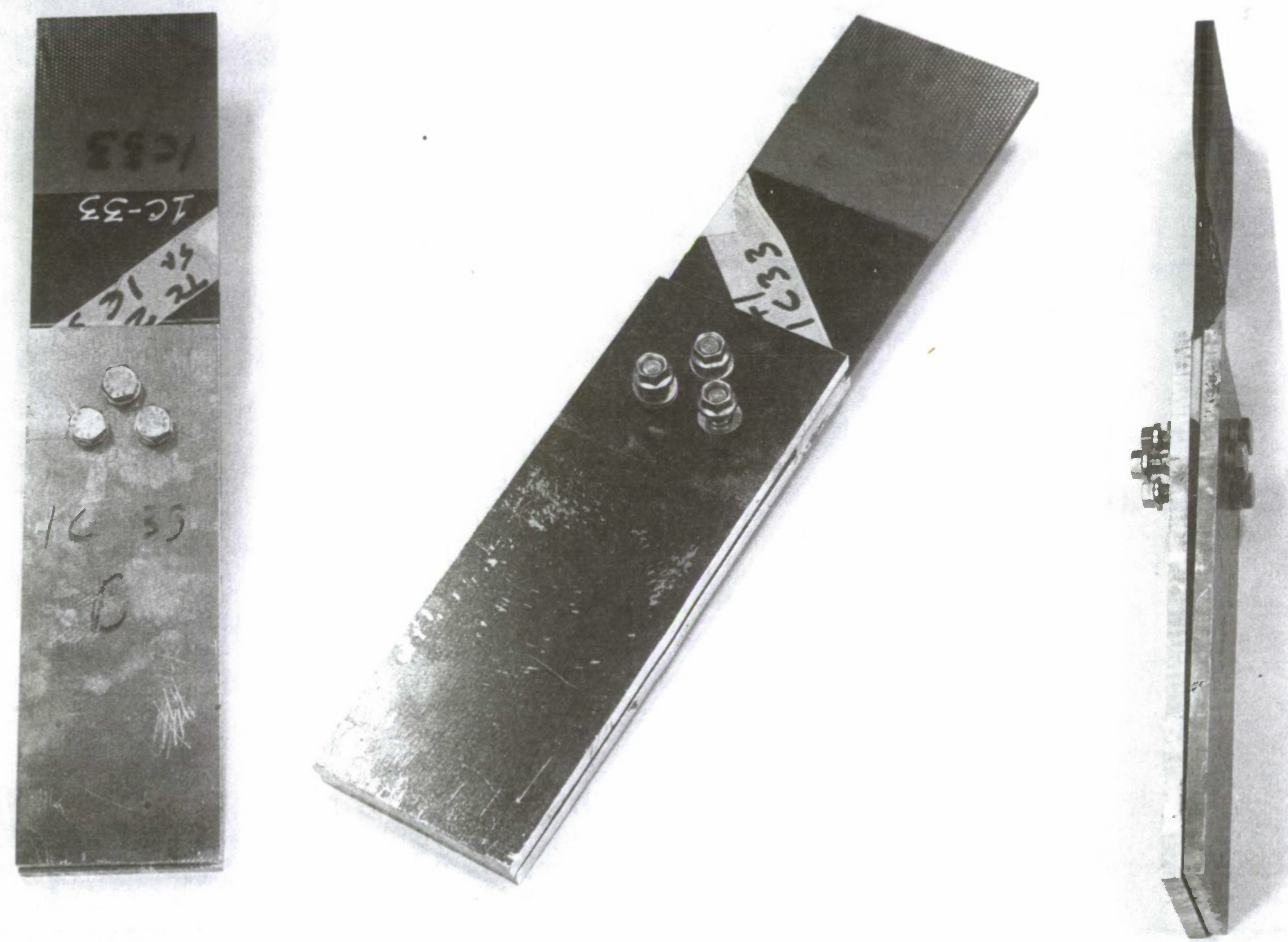
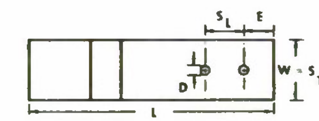
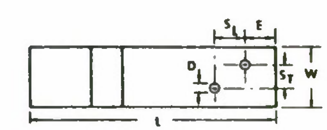


Figure 2-2. Sample Photographs of A Double Shear Test

TABLE 2-1. TASK II TESTS ON MULTIFASTENER JOINTS.

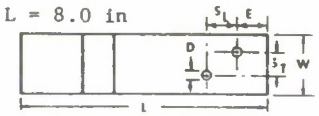
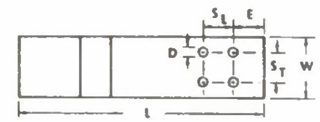
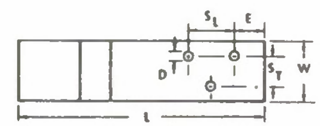
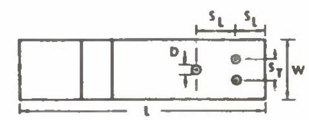
TEST CASE	SPECIMEN	% OF 0°, ±45°, AND 90° FIBERS	S_L/D	S_T/D	W/D	E/D	FASTENER	LOADING	COMPOSITE/ METAL GEOMETRY	COMMENTS*	SCHEMATIC
201	1A29, 1A44, 1A59, 1A36, 1A51, 1A37, 1A52, 1A17	50/40/10	4	6	6	3	51B464-5	ST	1		
202	2.6, 2.8, 2.10	70/20/10									
203	3.6, 3.8, 3.10	30/60/10									
204	1A30, 1A45, 1A60	50/40/10					51B335			CSK	
205	1A31, 1A46, 1A61							SC		CSK	
206	1A32, 1A47, 1A15						51B464-5	ST	2	DL	
207	1A33, 1A48, 1A63								2	DL, ETW	
208	1A34, 1A49, 1A64								1	ETW	
209	1A35, 1A50, 1A65							SC	1	ETW	L = 8.0 in
210	1A66, 1A40, 1A55, 1A12							ST		T=0	
211	1A67, 1A41, 1A56, 1A20									T=200	
212	1A38, 1A53, 1A68		3						3		
213	1A39, 1A54, 1A69		2						4		
214	2.7, 2.9, 2.11	70/20/10									
215	3.7, 3.9, 3.11	30/60/10	2	6	6	3	51B464-5	ST	4		
216	1B19, 1B21, 1B23	50/40/10	2	2	8	3	51B464-5	ST	5		
217	1B25, 1B27, 1B29								6	DL	
218	1B30, 1B39, 1B41									DL, ETW	
219	1B28, 1B36, 1B38							SC		DL	
220	1D4, 1D5, 1D6		3	3	9			ST	7		
221	1D1, 1D2, 1D3		4	4	10	3			8		L = 8.0 in

*For all test cases Diameter = 5/16 inch (PH); Torque = 100 in-lb; Test Environment is RTD; and Joint Type is Single-Lap (SL) unless otherwise noted.

ST = Static Tension — PH = Protruding Head — SL = Single-Lap — RTD = Room Temperature Dry

SC = Static Compression — CSK = 100° Countersink Tension Head — DL = Double-Lap — ETW = Elevated Temperature Wet

TABLE 2-1. TASK II TESTS ON MULTIFASTENER JOINTS, (CONTINUED).

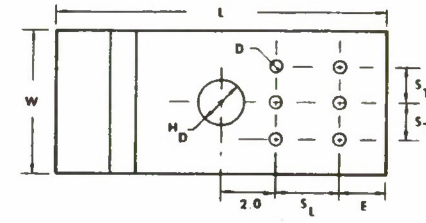
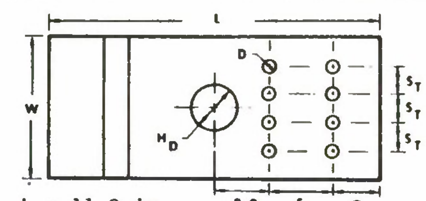
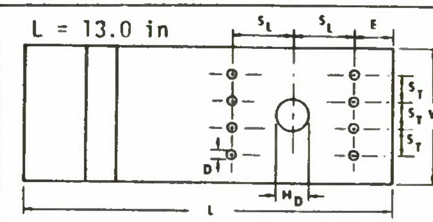
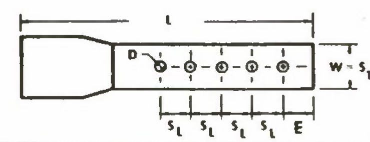
TEST CASE	SPECIMEN	% OF 0°, -45°, AND 90° FIBERS	S_L/D	S_T/D	W/D	E/D	FASTENER	LOADING	COMPOSITE/ METAL GEOMETRY	COMMENTS*	SCHEMATIC
222	1B32, 1B34, 1B40	50/40/10	2	2	B	3	51B335	ST	5	CSK	L = 8.0 in 
223	2.12, 2.13, 2.14	70/20/10	↓	↓	↓	↓	51B464-5	↓	6	DL	
224	3.12, 3.13, 3.14	30/60/10	↓	↓	↓	↓	↓	↓	↓	DL	
225	1B1, 1B3, 1B5	50/40/10	4	4	10	3	51B464-5	ST	9		
226	1B2, 1B4, 1B6	↓	↓	↓	↓	↓	↓	↓	10	DL	
227	1B7, 1B9, 1B11	↓	↓	↓	↓	↓	↓	↓	↓	DL, ETW	
228	1B8, 1B10, 1B12	↓	↓	↓	↓	↓	51B335	↓	9	CSK	
229	2.1, 2.2, 2.3	70/20/10	↓	↓	↓	↓	51B464-5	↓	↓		
230	3.1, 3.2, 3.3	30/60/10	↓	↓	↓	↓	↓	↓	↓	L = 8	
231	1C2, 1C4, 1C6	50/40/10	3	3	9	↓	↓	ST	11		L = 8.0 in
232	1B13, 1B15, 1B17	50/40/10	4	4	10	3	51B335.	SC	9	CSK	
233	1CB, 1C10, 1C11	50/40/10	4	3	9	3	51B464-5	ST	12		
234	1C13, 1C15, 1C17	↓	↓	↓	↓	↓	↓	↓	13	DL	
235	1C19, 1C21, 1C23	↓	↓	↓	↓	↓	↓	↓	↓	DL, ETW	
236	1C20, 1C22, 1C24	↓	↓	↓	↓	↓	51B335	↓	12	CSK	
237	1C25, 1C27, 1C29	↓	↓	↓	↓	↓	51B464-5	SC	13	DL	
238	2.4, 2.5, 2.15	70/20/10	↓	↓	↓	↓	↓	ST	↓	DL	L = 8.0 in
239	3.4, 3.5, 3.15	30/60/10	↓	↓	↓	↓	↓	↓	↓	DL	
240	1C26, 1C28, 1C30	50/40/10	2	3	9	3	↓	ST	14	DL	
241	1C31, 1C33, 1C35	50/40/10	2	3	9	3	51B464-5	SC	14	DL	L = 8.0 in

*For all test cases Diameter 5/16 inch (PH); Torque = 100 in-lb; Test Environment is RTD; and Joint Type is Single-Lap (SL) unless otherwise noted.

ST = Static Tension | PH = Protruding Head | SL = Single-Lap | RTD = Room Temperature Dry

SC = Static Compression | CSK = 100° Countersink Tension Head | DL = Double-Lap | ETW = Elevated Temperature Wet

TABLE 2-1. TASK II TESTS ON MULTIFASTENER JOINTS. (CONCLUDED).

TEST CASE	SPECIMEN	% OF 0°, ±45°, AND 90° FIBERS	S_L/D	S_T/D	W/D	E/D	FASTENER	LOADING	COMPOSITE/ METAL GEOMETRY	COMMENTS*	SCHEMATIC
242	10A4, 10B10, 10B12	50/40/10	4	8	14.4	3.2	51B464-5	ST	15	DL HD = 1.0	 L = 11.0 in.
243	10B11, 10B15, 10B17	↓	↓	↓	↓	↓	↓	↓	16	↓	
244	10B13, 10B14, 10B16						51B335		↓	CSK	
245	10B1, 10B2, 10B3						51B464-5	SC	17	DL, L = 9.5	
246	12.1, 12.2, 12.3	70/20/10					↓	ST	16		
247	14.1, 14.2, 14.3	25/60/15	4	8	14.4	3.2	51B464-5	ST	16	HD = 1.0	
248	10A1, 10A3, 10B4	50/40/10	4	4	16	3.2	51B464-5	ST	18	HD = 1.0	 L = 11.0 in
249	10A5, 10A6, 10A7	50/40/10	-	4	16	3.2	51B335	ST	19	CSK HD = 1.0	L = 13.0 in 
250	10A9, 10B6, 10B8	50/40/10	4	-	4.8	3.2	51B464-5	ST	20	DL	
251	10A10, 10A13, 10A16	↓	↓	-	↓	↓	↓	↓	21		
252	10A11, 10A14, 10A17			-			51B335		21	CSK	
253	10A12, 10A15, 10A18	50/40/10	4	-	4.8	3.2	↓	ST	21	CSK T = 250	

* For all test cases Diameter = 5/16 inch (PH); Torque = 100 in-lb; Test Environment is RTD; and Joint Type is Single-Lap (SL) unless otherwise noted.

ST = Static Tension
SC = Static Compression
PH = Protruding Head
CSK = 100° Countersink Tension Head
SL = Single-Lap
DL = Double-Lap
RTD = Room Temperature Dry
ETW = Elevated Temperature Wet

specimen width and edge distance (W and E, respectively), and cut-out diameter (H_D) and location, for the various test cases, are listed in Table 2-1.

2.4 Metal Plates

As in Reference 1-2, aluminum plates were bolted to laminates to effect load transfer in single and double shear configurations (see Figures 2-1 and 2-2). The metallic plates were machined from 7075-T7 raw stock, and contained fastener hole arrangements that were compatible with those in the laminated specimens (see Table 2-1 and Figures 2-1 and 2-2). Figure 2-3 presents the dimensions of the metal plates used in the various tests.

2.5 Fasteners

Most of the tests used 5/16 inch diameter, protruding head, steel fasteners (see Table 2-1). Selected tests in a single shear configuration used 5/16 inch diameter, 100^{o} countersunk (tension head), steel fasteners (see Table 2-1). In these cases, the holes in the laminates were countersunk to accommodate the flush head fasteners. The fasteners were torqued to 100 in-lbs, prior to testing, unless otherwise specified. Torque values of 0, 200 and 250 in-lbs were imposed in selected test cases (see Table 2-1).

2.6 Test Arrangement

The test arrangements for the static tensile and compressive tests were identical to those used for tests on single fastener joints (see Figures 2-4, 2-5 and Reference 1-2). Anti-buckling guides, similar to those used in Reference 1-2, were used when a compressive load was introduced, to preclude gross buckling in the test section. A heat chamber covered the test section during elevated temperature (218^{o}F) tests on wet (moisture absorbed) specimens.

2.7 Test Environment

Most of the tests were conducted under room temperature, dry (RTD) or ambient conditions. Selected tests on 20-ply laminates were conducted under elevated temperature (218^{o}F), wet (ETW) conditions (see Table 2-1). ETW test specimens were preconditioned, prior to testing, at 170%, 95% relative humidity conditions for approximately 40 days. Moisture data were gathered

COMPOSITE METAL GEOMETRY*	t_1	t_2	L	a
1	.31	.73	7.5	2.25
2	.26	--	7.5	--
3	.31	.73	6.5	1.52
4	.31	.73	6.5	1.21
5	.31	.73	7.5	2.88
6	.26	--	8.0	--
7	.31	.73	8.0	3.06
8	.31	.73	8.0	2.75
9	.31	.73	8.0	2.75
10	.26	--	8.0	--
11	.31	.73	8.0	3.06
12	.31	.73	8.0	2.75
13	.26	--	8.0	--
14	.26	--	8.0	--
15	.38	--	8.0	--
16	.50	1.25	10.0	4.75
17	.38	--	8.0	--
18	.50	1.25	8.0	2.75
19	.50	1.25	12.0	4.00
20	.38	--	10.0	--
21	.50	1.25	10.5	1.5

All dimensions in inches
*See Table 2-1 for applicable test cases

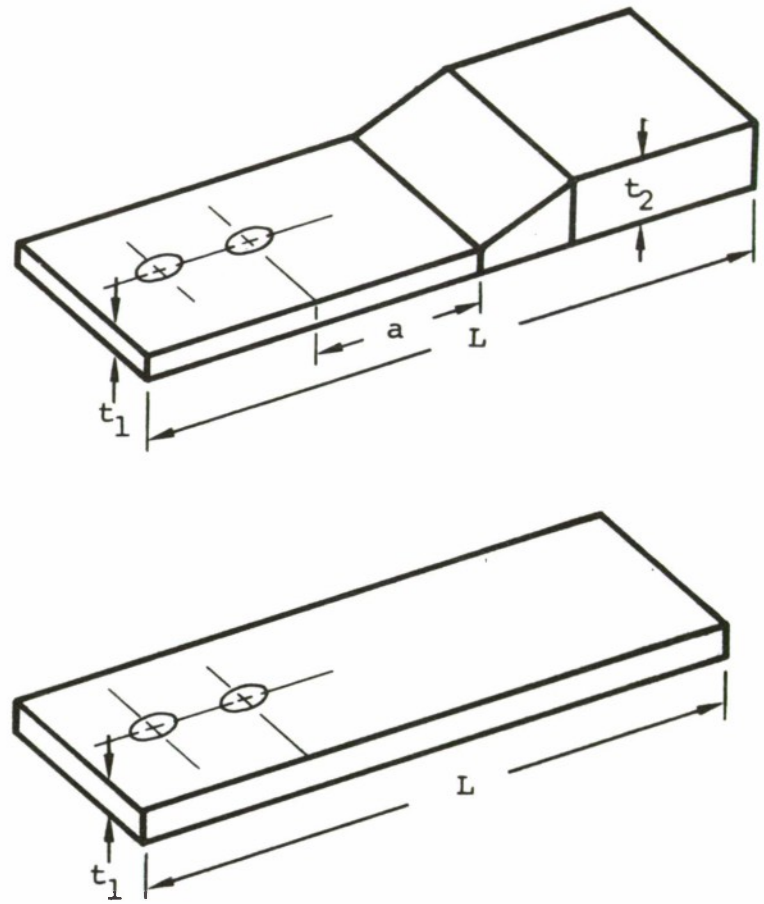


Figure 2-3. Dimensions of the Metal Plates for the Various Composite-To-Metal Multifastener Joints.

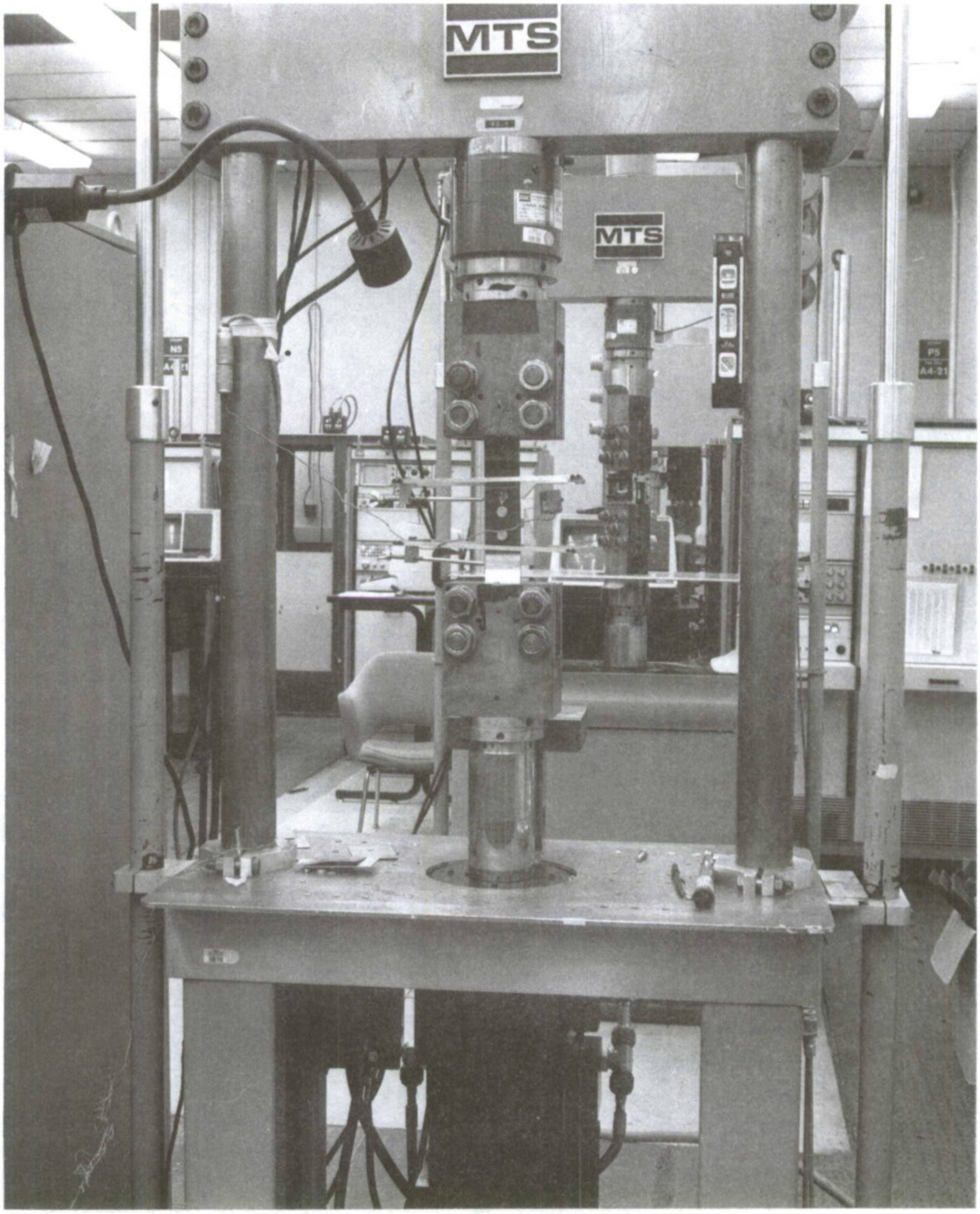


Figure 2-4. Test Arrangement for Static Tensile Tests.

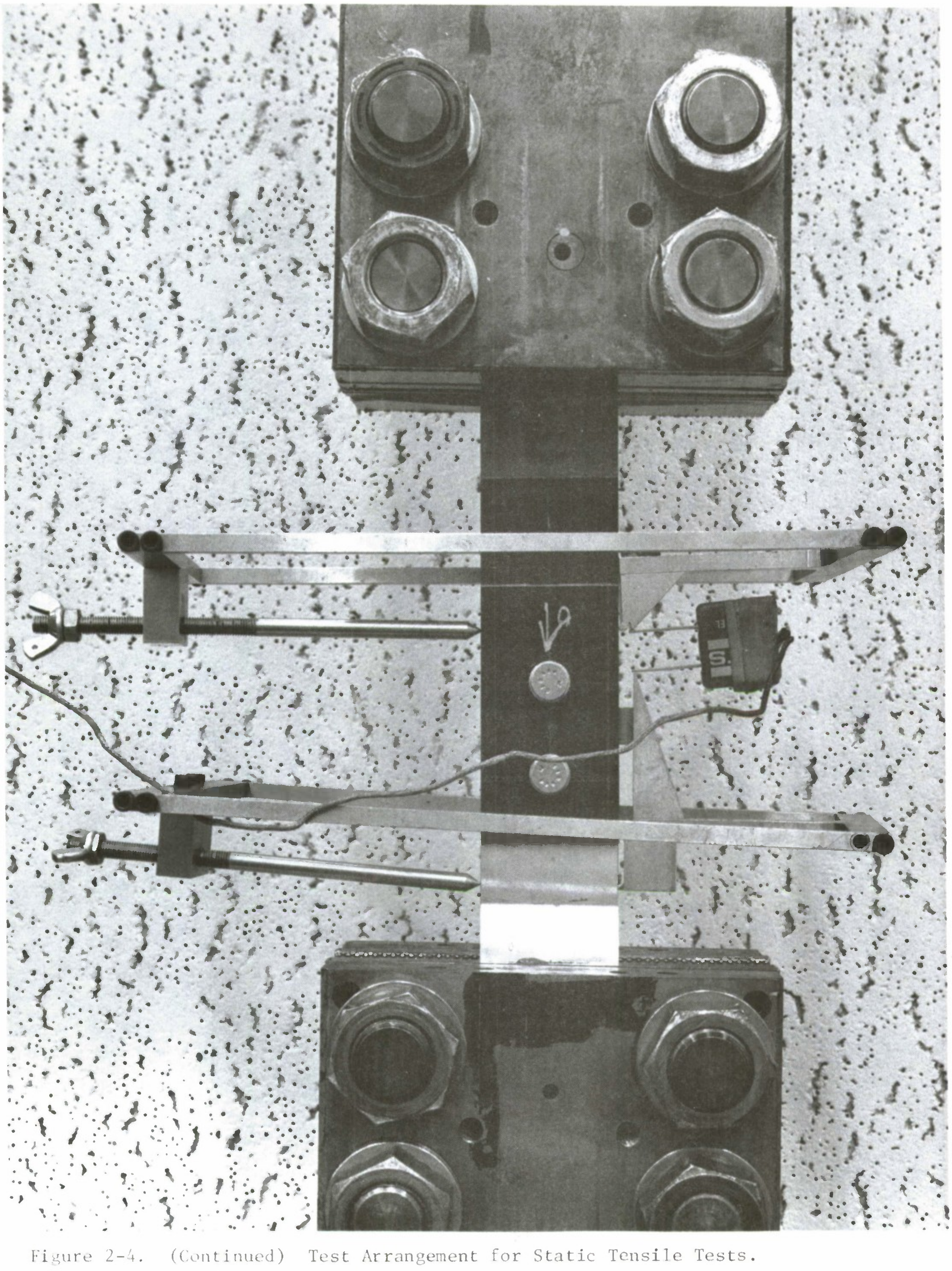


Figure 2-4. (Continued) Test Arrangement for Static Tensile Tests.

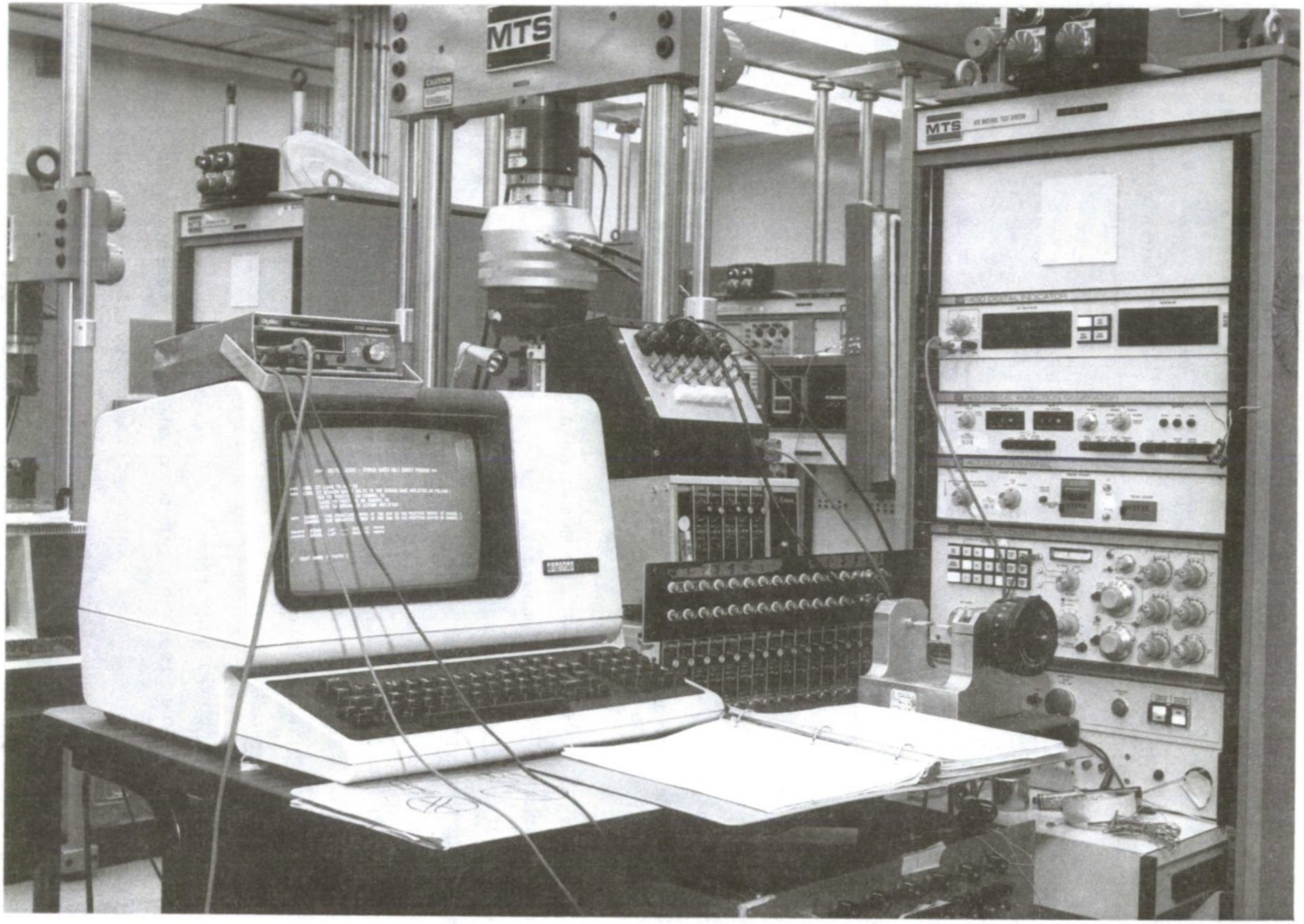


Figure 2-5. Computerized Support System Used for Test Control, Data Acquisition and Data Processing.

on eighteen one-inch square traveler specimens that accompanied the test specimens during the preconditioning cycle. The measured moisture contents varied from 0.6 to 0.78% by weight, with an average value of 0.7%. This value is lower than the anticipated value of nearly 1%, and the cause for the difference was belatedly traced back to technical difficulties in maintaining the temperature and humidity levels in the chamber.

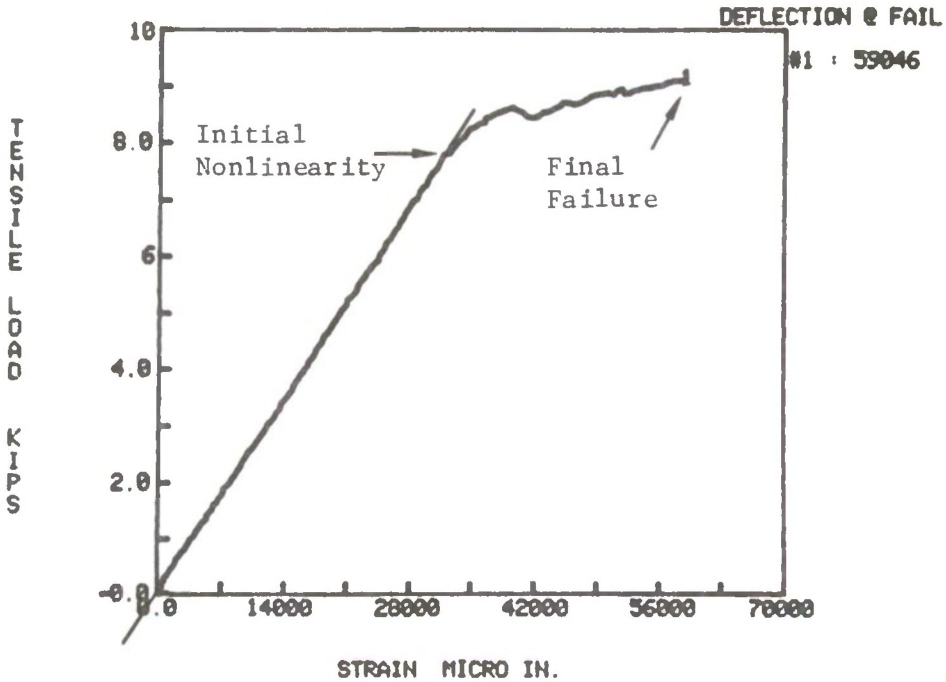
2.8 Test Measurements

Prior to testing, the actual dimensions of the laminated and metallic specimens were measured, to record any change from the values listed in Table 2-1. During the tests, the applied load, the remote axial strain (in the load direction), and the overall joint deflection were monitored. Back-to-back axial strain gages were mounted near the specimen tabs boundary to measure the remote strain values. The gages were located one inch away from the tab edge in most of the specimens. In specimens with a cut-out (test cases 242 to 248 in Table 2-1), the strain gages were located only half an inch away from the tab edge, to maintain a distance of two diameters from the center of the cut-out hole.

The overall joint deflection was measured using an extensometer (clip gage). The extensometer measured the deflection between fully-loaded cross-sections in the metallic and laminated specimens. The extensometer gage length was recorded along with the measured deflections. In contrast to Reference 1-2, the load versus extensometer deflection plots provide the total joint stiffness values, not the stiffness corresponding to load transfer across a single fastener. Sample load versus extensometer deflection plots are presented in Figure 2-6. The total joint stiffness is measured by computing the slope of the initial (linear) part of each of these curves.

In addition to the above measurements, a unique Northrop-developed technique (Reference 2-2) was also employed to obtain direct measurements of the fastener loads in the test specimens. This technique obviates the need for the uneconomical use of many strain gages between adjacent fasteners, normally resorted to by other investigators. It also provides results that are useful and necessary in assessing the validity of analytical predictions. A brief description of this technique is presented below.

Test Case 201; Specimen 1A36
Tension; Single-Lap; (2) PH Fasteners
Geometry 1; RTD



Test Case 218; Specimen 1B30
Tension; Double-Lap; (2) PH Fasteners
Geometry 6; ETW

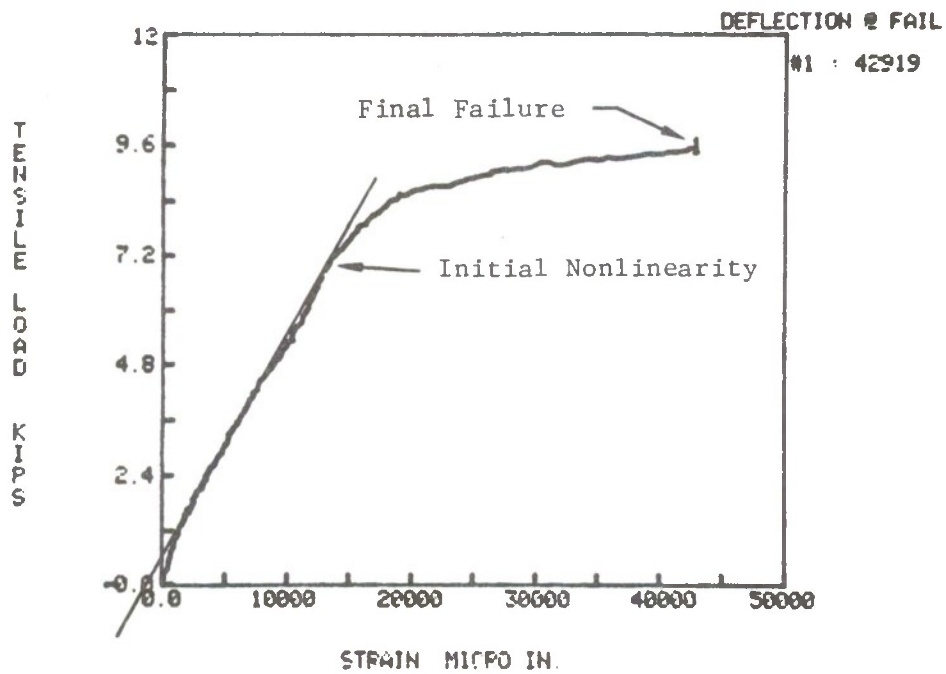
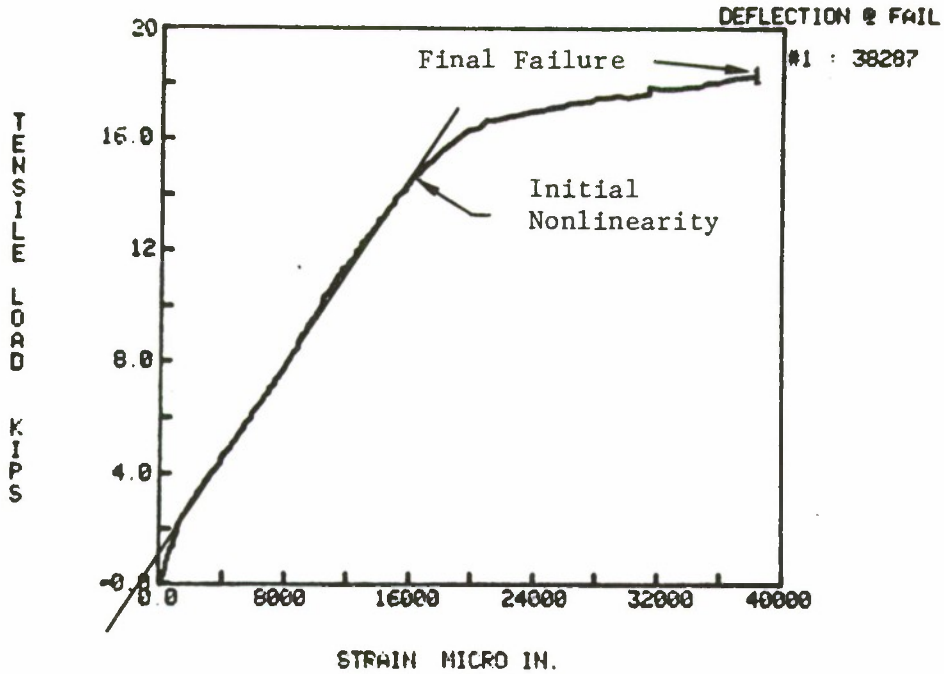


Figure 2-6. Typical Load Versus Clip-Gage Deflection Plots from Static Tests

Test Case 227; Specimen 1B7
Tension; Double-Lap; (4) PH Fasteners
Geometry 10; ETW



Test Case 235; Specimen 1C19
Tension; Double-Lap; (3) PH Fasteners
Geometry 13; ETW

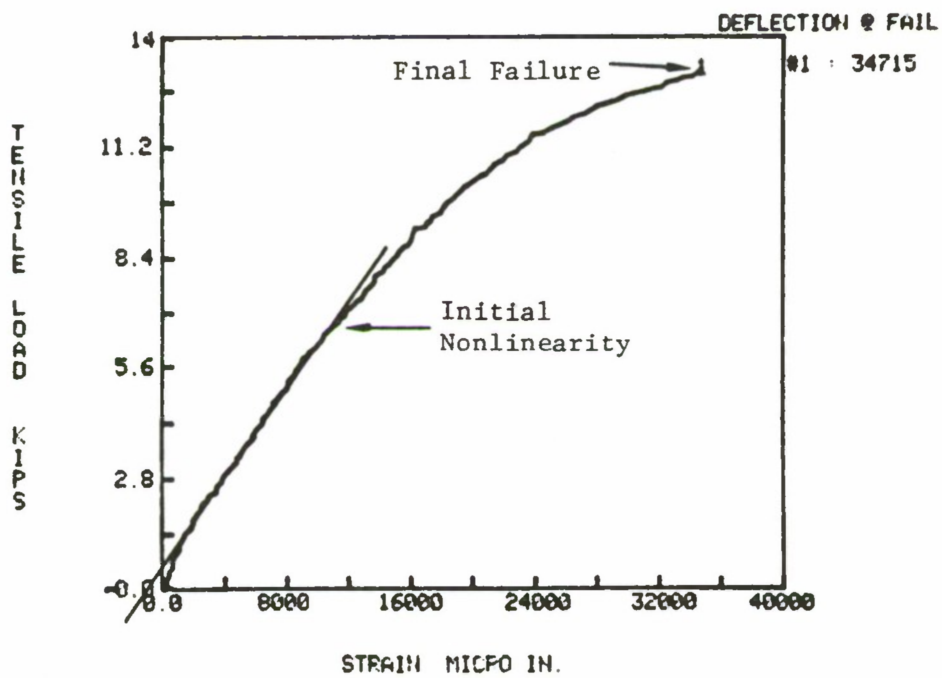
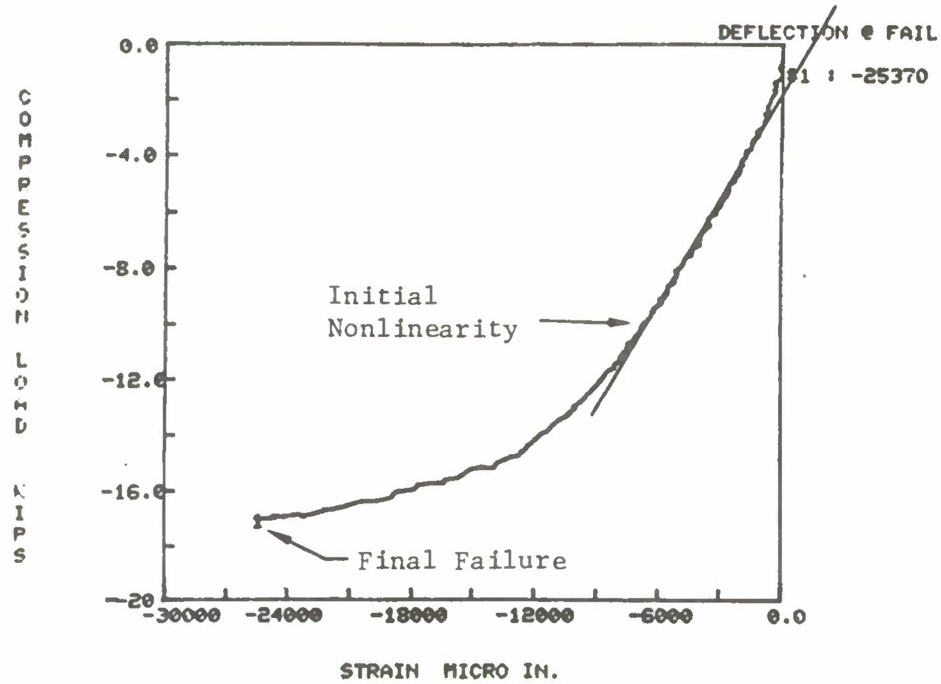


Figure 2-6. Typical Load Versus Clip-Gage Deflection Plots from Static Tests. (Continued)

Test Case 237; Specimen 1C25
Compression; Double-Lap; (3) PH Fasteners
Geometry 13; RTD



Test Case 241; Specimen 1C31
Compression; Double-Lap; (3) PH Fasteners
Geometry 14; RTD

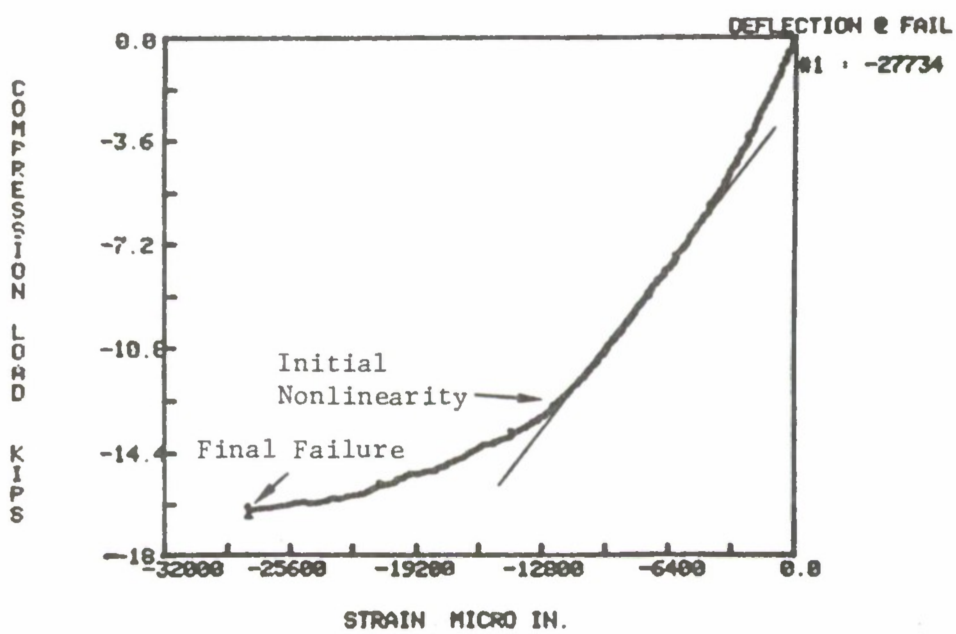
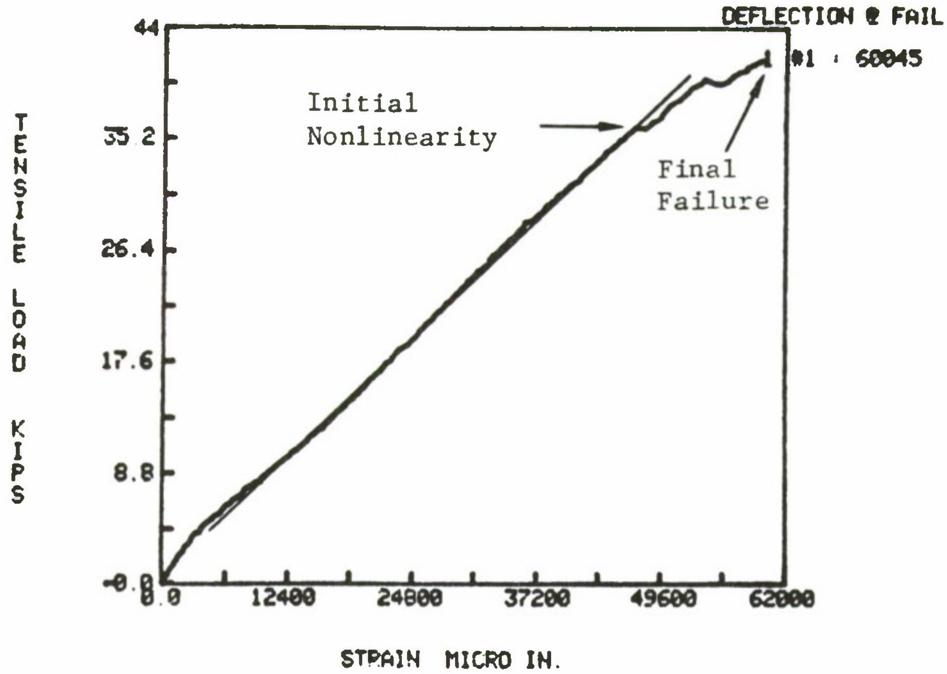


Figure 2-6. Typical Load Versus Clip-Gage Deflection Plots from Static Tests. (Continued)

Test Case 243; Specimen 10B11
Tension; Single-Lap; (6) PH Fasteners
Geometry 16; RTD



Test Case 247; Specimen 14.1
Tension; Single-Lap; (6) PH Fasteners
Geometry 16; RTD

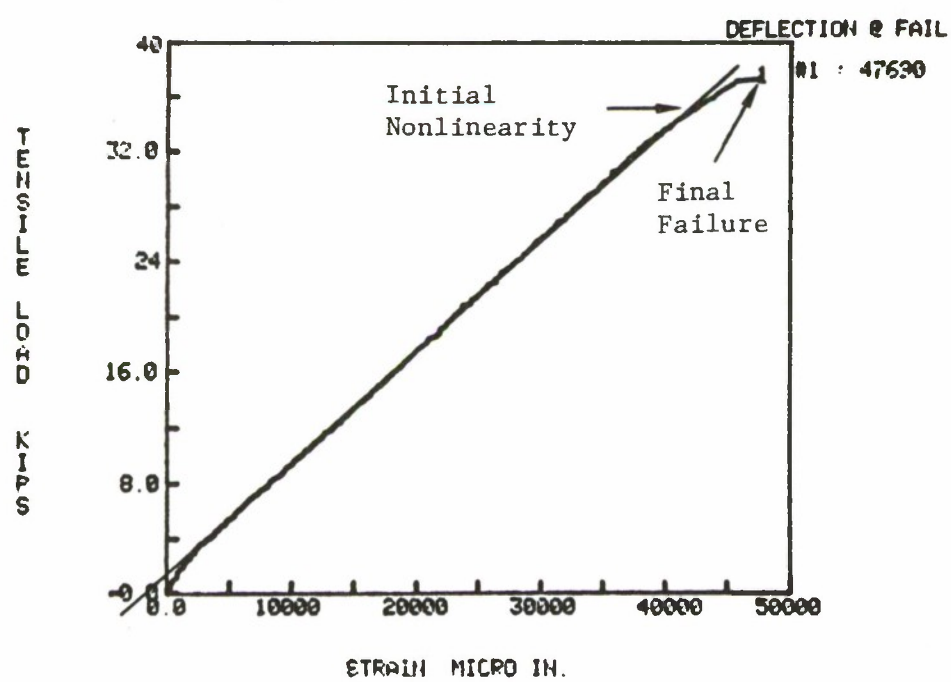


Figure 2-6. Typical Load Versus Clip-Gage Deflection Plots From Static Tests. (Continued)

Test Case 251; Specimen 10A10
Tension; Single-Lap; (5) PH Fasteners
Geometry 21; RTD

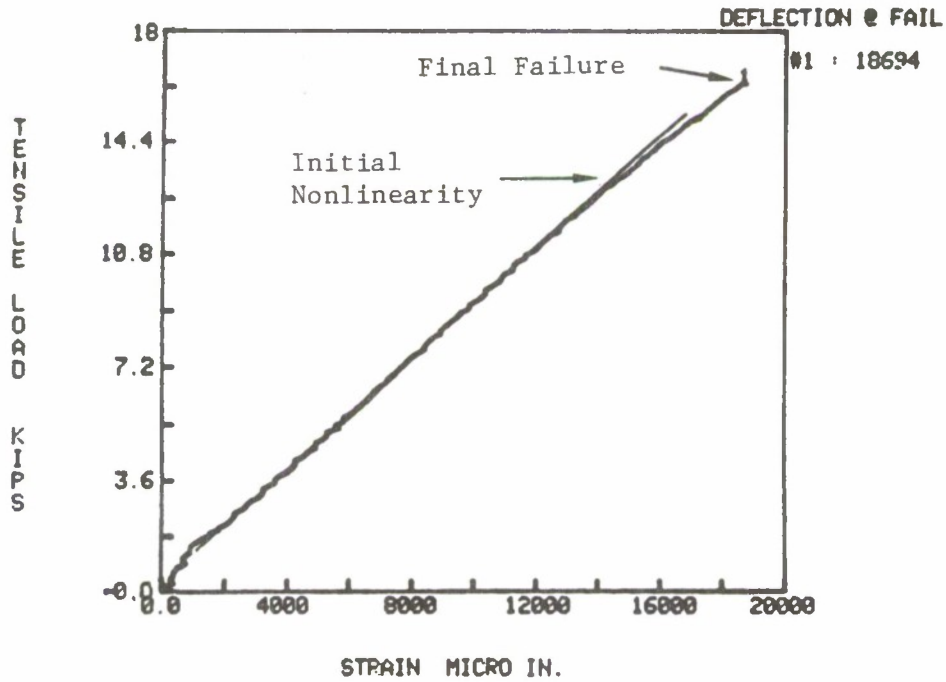


Figure 2-6. Typical Load Versus Clip-Gage Deflection Plots from Static Tests. (Concluded)

2.9 Fastener Load Measurement Using Strain-Gaged Bolts

The load distribution among the fasteners in a bolted plate has hitherto been experimentally measured using strain gages. This generally involves the use of many gages that are bonded to either surface of the bolted plate. Computations based on strain gage readings only provide an approximate measurement of the load transferred by every row of fasteners. In contrast, the experimental technique developed in Reference 2-2 provides a more efficient and economical procedure for an accurate measurement of the load at every fastener location.

The technique developed in Reference 2-2 involves the use of strain-gaged bolts (see Figure 2-7). The individual strain gages sense the local shearing and bending effects, and the stress concentration effects at the surface where they are located (see Reference 2-3). Calibration tests are initially performed to derive analytical expressions that compute the magnitude and orientation of the fastener load in a general situation. The difference between the calibration situation, where the magnitude and orientation of the applied load is known, and the general application situation, where neither the magnitude nor the orientation of the load is known, is illustrated in Figure 2-8.

In the general situation, the strain-gaged bolt is one among many in a bolted plate, and its output (ΔV in volts) is dependent on the magnitude of the load (P) and its orientation (α) with respect to the reference direction ($\theta = 0^{o}$). The following mathematical expression applies in this situation:

$$\Delta V = \left[\sum_{i=1}^{n} \{ A_i \text{ Cos } i\ (\theta+\alpha) + B_i \text{ Sin } i\ (\theta+\alpha) \} \right] (P-P_o)/(P_c-P_o)$$

where P_c is the calibration load and A_i, B_i and P_o are constants obtained from calibration test results. By measuring the bolt outputs (ΔV_1 and ΔV_2) at two orientation (θ_1 and θ_2) and incorporating these results into the above equation, P and α at the bolt location can be computed. N was assumed to be 4 in Reference 2-2.

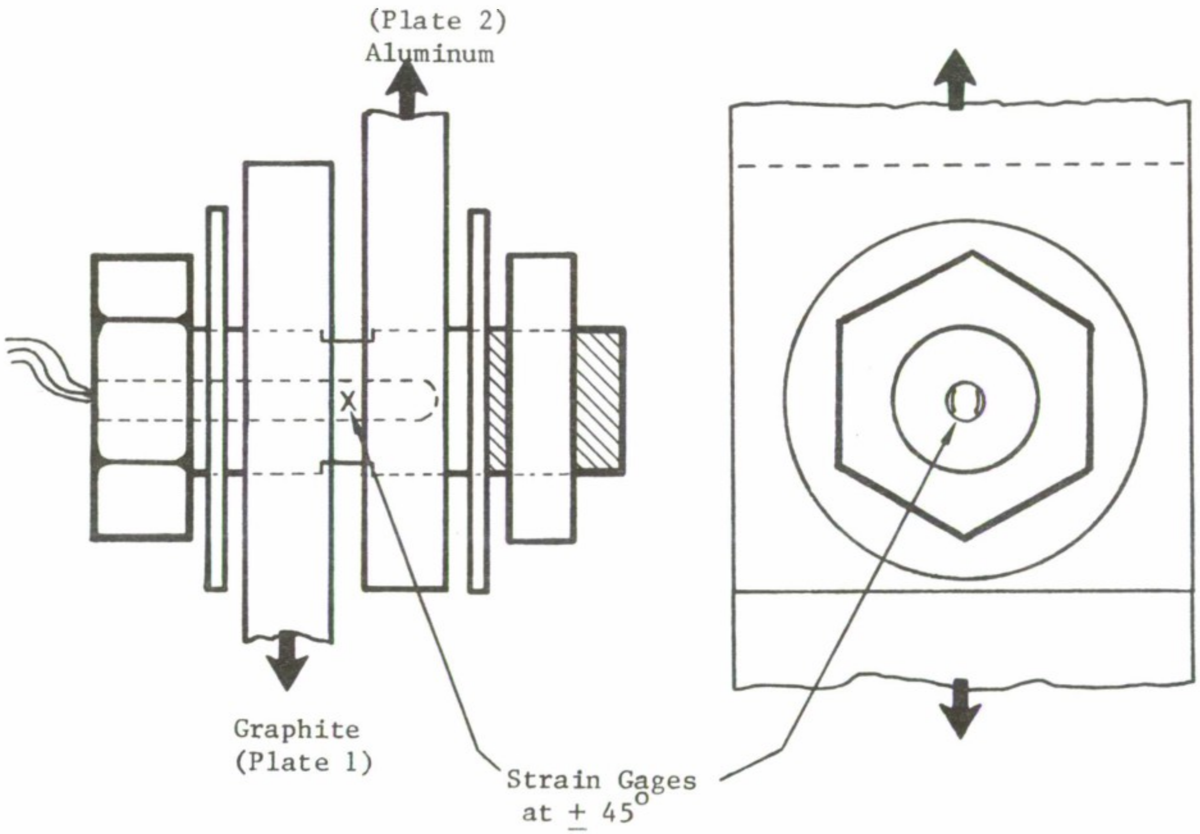


Figure 2-7. Schematic Diagram of the Strain-Gaged Bolt in a Single Shear Test Setup.

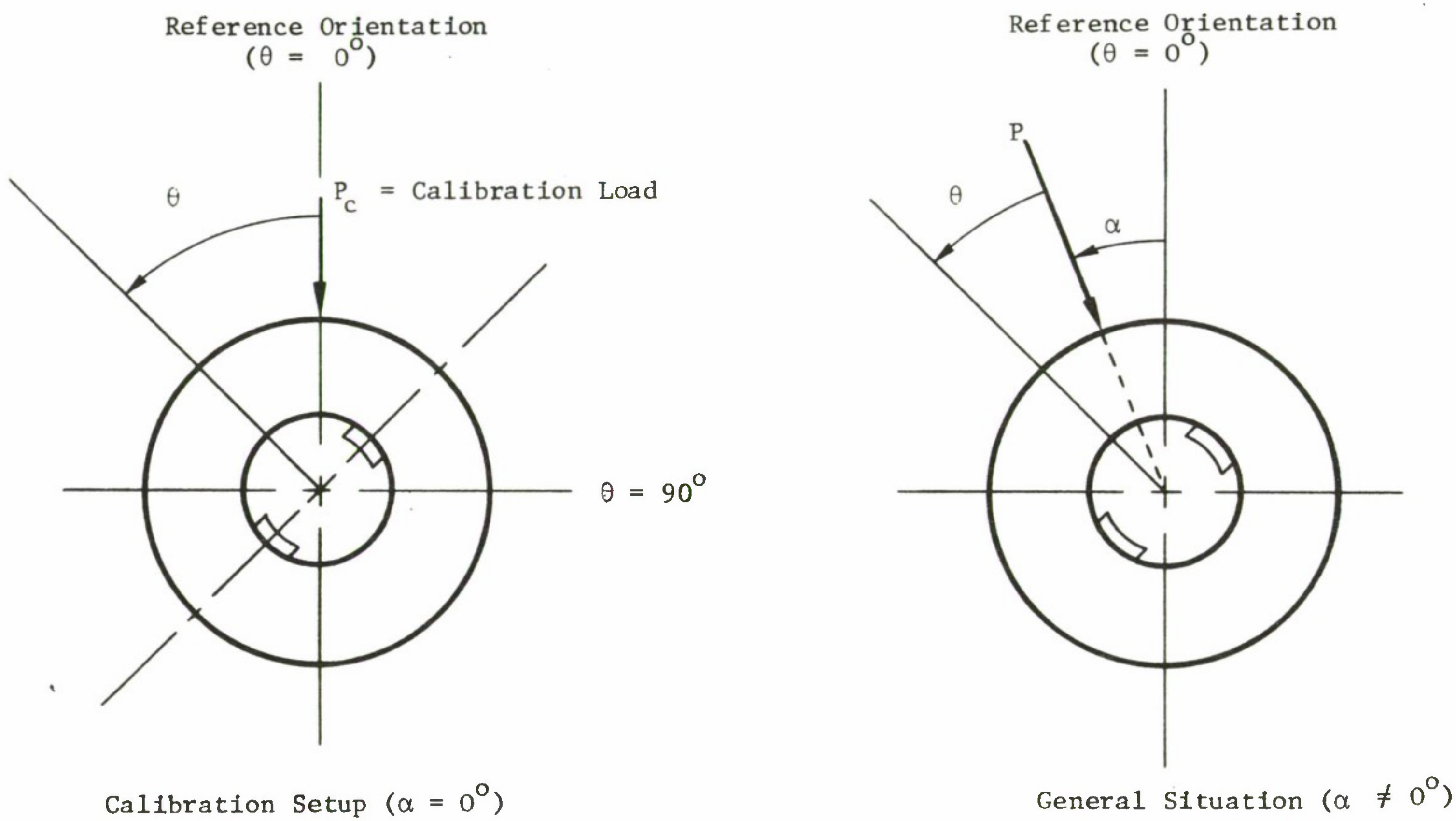


Figure 2-8. Assumed Reference Orientation for the Fastener Load and Its Relationship to the Gage Location.

One replicate from each test case in Table 2-1 was initially fastened together using calibrated strain-gaged bolts. Bolt outputs (ΔV_1 and ΔV_2) were recorded corresponding to two bolt orientations (θ_1 and θ_2), at the same survey load level (see Figure 2-9). Using these measurements, the magnitude and orientation of the load was computed at every strain-gaged bolt location. The strain-gaged bolts were replaced by regular fasteners after the load distribution was determined, and the load was increased beyond the survey load level to measure the joint strength.

Sample multifastener test cases from this program were studied in Reference 2-2, using strain-gaged bolts and the described load measurement technique. Predicted fastener loads satisfied equilibrium conditions reasonably well, and the computed load orientations generally agreed with intuition.

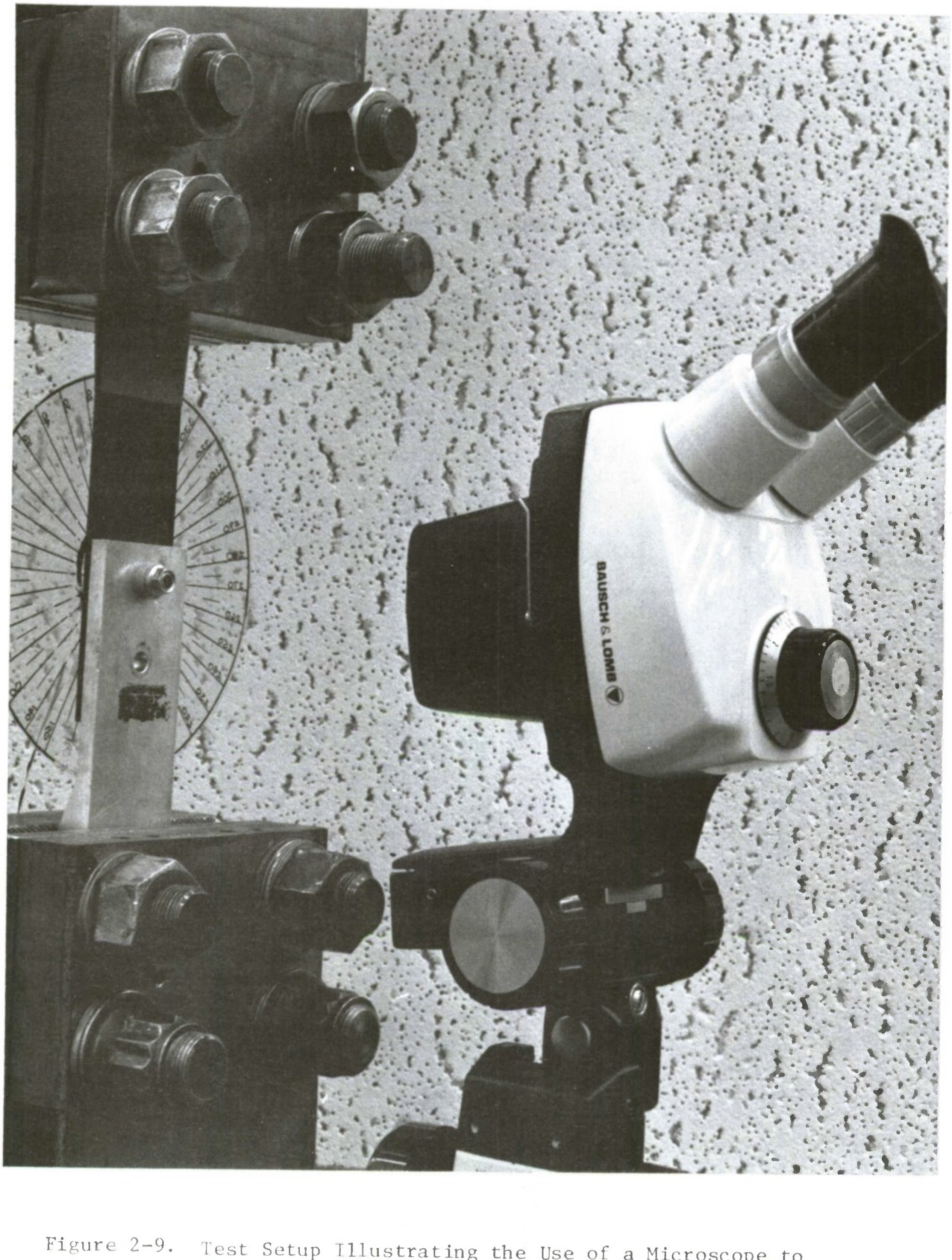


Figure 2-9. Test Setup Illustrating the Use of a Microscope to Accurately Rotate the Strain-Gaged Bolts.

SECTION 3

MULTIFASTENER JOINT TEST RESULTS

A summary of the results from the various tests on multifastener composite-to-metal joints (listed in Table 2-1) is presented in Table 3-1. The following sub-sections discuss these results, proceeding from two fasteners in tandem to a fastener arrangement that includes eight fasteners and a neighboring circular cut-out.

3.1 Results from Tests on Joints with Two Fasteners in Tandem

Test cases 201 to 215 in Table 2-1 address composite-to-metal joints with two fasteners in tandem (along the loading direction). 20-ply laminates, with a 50/40/10, 70/20/10 or 30/60/10 layup were tested in a single or double shear configuration (see Figures 2-1 and 2-2). The corresponding aluminum plate dimensions are listed in Figure 2-3. With the exception of two test cases, all the static tests were conducted under tension. Countersunk, 5/16 inch diameter steel fasteners were used in two test cases. Three test cases were conducted under ETW (218^{o}F, wet) conditions. In two test cases, the fasteners were torqued to 200 in-lbs or were untorqued (finger-tight). The spacing between the two fasteners in the load direction (S_L) was varied from 2 to 4, while the specimen width (W), edge distance (E) and hole diameter (D) were held constant. In the laminates, W/D was 6, E/D was 3, and D was 5/16 inch. Joint failure was precipitated by laminate failure in every case. Failed laminates were examined to identify the predominant failure mode(s). Table 3-1 contains failure mode identification numbers that were introduced in Reference 1-2 (see Figure 3-1).

Static tension tests on 50/40/10, 70/20/10 and 30/60/10 laminates with $S_L/D = 4$ produced the results shown in Table 3-1. The 50/40/10 laminate suffered a local bearing mode of failure in most of the tests, though partial shear-out was identified in one replicate (see Figure 3-2). The 70/20/10 laminates suffered a partial shear-out mode of failure (Figure 3-3). The 30/60/10 laminates suffered a local bearing mode of failure in two tests, and a net section mode of failure in one test (Figure 3-4). Strain-gaged bolts predicted that each fastener carried approximately 50% of the applied load (see Figure 3-5).

TABLE 3.1 SUMMARY OF TASK II TEST RESULTS

TEST CASE	SPECIMEN ID.	GEOMETRY NUMBER*	FAILURE MODE**	LOAD VS DEFLECTION		TOTAL FAILURE		NOMINAL GROSS WIDTH (IN)	ACTUAL THICKNESS (IN)	GROSS AREA (IN^2)
				PROPORTIONAL LIMIT (KIPS)	SLOPE (KIPS/IN)	LOAD (KIPS)	GROSS STRAIN μIN/IN			
201	1A17	1	3,4	-	-	9.490	-	1.876	.113	.212
	1A59		2,4,5,8	8.1	263	9.555	-		.113	.212
	1A29		3,4	-	-	9.465	4182		.113	.212
	1A44		3,4	-	-	9.599	-		.114	.214
	1A36		3,4	7.8	279	9.135	4064		.114	.214
	1A51		3,4	-	-	9.492	-		.112	.210
	1A37		3,4	6.2	218	9.526	4197		.113	.212
	1A52		3,5	-	-	9.831	-		.113	.212
202	2.6	1	2,4,5	7.3	303	8.195	2946		.108	.203
	2.8		2,4,5	-	-	7.706	-		.108	.203
	2.10		2,4,5	-	-	7.855	-		.107	.201
203	3.6	1	3,4	7.8	246	9.367	5675		.106	.199
	3.8		7,8,5	-	-	9.697	-		.106	.199
	3.10		3,4	-	-	7.697	-		.106	.199
204	1A30	1	2,5,8	-	-	9.399	-		.116	.218
	1A45		3,4	8.0	120	8.911	3611		.114	.214
	1A60		2,5,8	-	-	8.813	3648		.114	.214
205	1A31	1	3,4	-6.3	226	-8.324	3693		.114	.214
	1A46		3,4	-	-	-9.233	-		.115	.216
	1A61		3,4	-	-	-9.301	-		.114	.214
206	1A32	2	6,5	5.5	111	8.896	3901		.114	.214
	1A47		7	-	-	10.454	-		.114	.214
	1A15		6,5	-	-	9.438	-		.114	.214
207	1A33	2	3	7.5	429	9.819	4583		.116	.218
	1A48		3	-	-	9.809	-		.113	.212
	1A63		3	-	-	9.760	-		.117	.219
208	1A34	1	3,4	4.5	250	6.414	Gage Fail		.113	.212
	1A49		3,4	-	-	7.445	-		.113	.212
	1A64		3,4	-	-	7.455	3502		.116	.218
209	1A35	1	9	-	-	-7.318	-		.114	.214
	1A50		9	-	-	-7.532	-		.115	.216
	1A65		9	-6.8	333	-8.295	-		.115	.216

TABLE 3.1 SUMMARY OF TASK II TEST RESULTS (CONTINUED).

TEST CASE	SPECIMEN ID.	GEOMETRY NUMBER*	FAILURE MODE**	LOAD VS DEFLECTION		TOTAL FAILURE		NOMINAL GROSS WIDTH (IN)	ACTUAL THICKNESS (IN)	GROSS AREA (IN^2)
				PROPOR-TIONAL LIMIT (KIPS)	SLOPE (KIPS/IN)	LOAD (KIPS)	GROSS STRAIN µIN/IN			
210	1A12	1	3,4	-	-	8.388	-	1.876	.110	.206
	1A66		3,4	-	-	7.992	-		.115	.216
	1A40		1,4,5	6.8	247	9.170	4194		.115	.216
	1A55		3,4	-		8.798	-		.113	.212
211	1A20	1	7	-	-	10.198	-		.113	.212
	1A67		3,4,13	-	-	10.601	-		.115	.216
	1A41		3,4,13	8.0	303	9.839	4198		.115	.216
	1A56		3,4,13	-	-	10.479	-		.113	.212
212	1A38	3	6,8,13	7.5	227	8.439	3832		.113	.212
	1A53		2,4,8	-	-	9.330	-		.113	.212
	1A68		6,8,13	-	-	9.306	-		.113	.212
213	1A39	4	6,13,8	7.7	286	8.219	3408		.115	.216
	1A54		6,13,8	-	-	8.903	-		.112	.210
	1A69		6,13,8	-	-	9.189	-		.111	.208
214	2.7	4	2,4,8,13	6.4	211	6.448	2371		.107	.201
	2.9		2,4,8,13	-	-	6.778	-		.107	.201
	2.11		2,4,8,13	-	-	6.815	-		.104	.195
215	3.7	4	2,8	7.4	164	8.534	5240		.106	.199
	3.9		2,8	-	-	8.989	-		.107	.201
	3.11		2,8	-	-	9.160	-		.105	.197
216	1819	5	2,6,5,8	8.7	238	9.130	3376		.118	.295
	1821		2,6,5,8	-	-	9.563	-		.117	.293
	1B23		2,6,5,8	-	-	9.355	-		.117	.293
217	1B25	6	6	NA	NA	9.319	3244		.117	.293
	1827		6	-	-	8.793	-		.115	.288
	1B29		6	-	-	9.025	-		.117	.293
218	1830	6	6,8	7.1	480	9.565	3394		.117	.293
	1839		6,8	-	-	9.135	-		.115	.288
	1B41		6,8	-	-	9.209	-		.117	.293
219	1B28	6	10	-	-	-9.184	-		.117	.293
	1B36		10	-	-	-11.539	-		.116	.290
	1838		10	-9.0	667	-11.295	-		.116	.290

TABLE 3.1 SUMMARY OF TASK II TEST RESULTS (CONTINUED).

TEST CASE	SPECIMEN ID.	GEOMETRY NUMBER*	FAILURE MODE**	LOAD VS DEFLECTION		TOTAL FAILURE		NOMINAL GROSS WIDTH (IN)	ACTUAL THICKNESS (IN)	GROSS AREA (IN^2)
				PROPOR-TIONAL LIMIT (KIPS)	SLOPE (KIPS/IN)	LOAD (KIPS)	GROSS STRAIN μIN/IN			
220	1D4	7	3,1,4	8.0	303	9.428	3047	2,813	.113	.318
	1D5		3,1,4	-	-	9.698	-		.113	.318
	1D6		3,1,4	-	-	9.946			.113	.31B
221	1D1	8	1,4,5	NA	NA	9.965	2829	3.125	.112	.350
	102		1,4,5	-	-	9.893	-		.113	.353
	1D3		3,4,2	-	-	9.245	-		.113	.353
222	1B32	5	6,5,8	3.5	340	7.386	2547	2,500	.116	.290
	1B34		6,5,8	-	-	7.513	-		.116	.290
	1B40		6,5,B	-	-	7.963	-		.117	.293
223	2.12	6	2,5	NA	NA	7.279	2102	2.500	.109	.273
	2.13		2,5	-	-	7.951	-		.109	.273
	2.14		2,5	-	-	7.397	-		.108	.270
224	3.12	6	6	7.9	387	10.796	4891		.110	.275
	3.13		6	-	-	10.625	-		.109	.273
	3.14		6	9.4	357	10.076	4765		.109	.273
225	1B1	9	7,5,8	13.8	540	18.149	5154	3.125	.118	.369
	1B3		6,5,8	-	-	18.271	-		.117	.366
	1B5		6,5,B	-	-	14.973	-		.116	.363
226	1B2	10	7	14.4	783	15.950	4424		.116	.363
	1B4		7	-	-	14.863	-		.116	.363
	1B6		7	-	-	16.805	-		.115	.359
227	1B7	10	2,5,6,8	14.9	833	18.271	5342		.117	.366
	1B9		2,5,6,B	-	-	17.831	-		.116	.363
	1B11		2,5,6,8	-	-	18.173	-		.117	.366
228	1B8	9	6,5,8	12.6	273	15.645	4377	3.125	.115	.359
	1B10		6,5,8	-	-	15.046	-		.115	.359
	1B12		6,5,8	-	-	14.631	-		.117	.366
229	2.1	9	2,8,5	NA	NA	14.436	3327		.104	.325
	2.2		2,8,5	-	-	16.268	-		.105	.328
	2.3		2,8,5	-	-	14.118	-		.105	.32B
230	3.1	9	7,8	-	-	17.123	662B		.106	.331
	3.2		7,8	-	-	16.231	-		.106	.331
	3.3		7,8	14.5	333	15.975	-		.107	.334

TABLE 3.1 SUMMARY OF TASK II TEST RESULTS (CONTINUED).

TEST CASE	SPECIMEN ID.	GEOMETRY NUMBER*	FAILURE MODE**	LOAD VS DEFLECTION		TOTAL FAILURE		NOMINAL GROSS WIDTH (IN)	ACTUAL THICKNESS (IN)	GROSS AREA (IN^2)
				PROPORTIONAL LIMIT (KIPS)	SLOPE (KIPS/IN)	LOAD (KIPS)	GROSS STRAIN μIN/IN			
231	1C2	11	12,8	14.0	427	15.095	4694	2.813	.113	.318
	1C4		12,8	-	-	13.481	-		.114	.321
	1C6		7,8	-	-	15.254	-		.114	.321
232	1B13	9	9	-13.0	353	-17.025	-	3.125	.118	.369
	1B15		10	-	-	-15.926	-		.116	.363
	1B17		9	-	-	-17.660	-		.117	.366
233	1C8	12	6,5,8	9.6	315	13.654	4188	2.813	.115	.323
	1C10		6,8	-	-	13.996	-		.115	.323
	1C11		3,4,8	-	-	11.517	-		.118	.332
234	1C13	13	12	-	-	11.705	3580		.117	.329
	1C15		12	-	-	12.272	-		.117	.329
	1C17		12	10.0	1140	12.877	-		.117	.329
235	1C19	13	6,5	NA	NA	13.166	4183	2.813	.115	.323
	1C21		6,5	-	-	13.229	-		.115	.323
	1C23		6,5	-	-	13.434	-		.115	.323
236	1C20	12	7	NA	NA	11.346	3230		.116	.326
	1C22		6,5,8	-	-	12.301	-		.116	.326
	1C24		6,5,8	-	-	11.334	-		.117	.329
237	1C25	13	3,10	-10.0	1250	-17	-		.117	.329
	1C27		3,10	-	-	-16.927	-		.116	.326
	1C29		3,10,11	-	-	-16.414	-		.117	.329
238	2.4	13	2,5	11.6	729	12.494	3208		.108	.304
	2.5		2,5	-	-	13.727	-		.107	.301
	2.15		2,5	-	-	12.408	-		.107	.301
239	3.4	13	7,8	10.6	760	12.787	5338		.107	.301
	3.5		7,8	-	-	13.666	-		.107	.301
	3.15		7,8	-	-	13.276	-		.107	.301
240	1C26	14	2,5	NA	NA	9.917	3105	2.813	.116	.326
	1C28		2,5	-	-	11.273	-		.114	.321
	1C30		2,5	-	-	10.967	-		.116	.326
241	1C31	14	10	-12.6	830	-16.414	-5540		.114	.321
	1C33		10	-	-	-15.950	-		.115	.323
	1C35		10	-	-	-15.903	-		.114	.321

TABLE 3.1 SUMMARY OF TASK II TEST RESULTS (CONCLUDED).

TEST CASE	SPECIMEN ID.	GEOMETRY NUMBER*	FAILURE MODE**	LOAD VS DEFLECTION		TOTAL FAILURE		NOMINAL GROSS WIDTH (IN)	ACTUAL THICKNESS (IN)	GROSS AREA (IN^2)
				PROPORTIONAL LIMIT (KIPS)	SLOPE (KIPS/IN)	LOAD (KIPS)	GROSS STRAIN μIN/IN			
242	10A4	15	7,8	-	-	39.814	-	4.500	.230	1.035
	10B10		7,8	-	-	43.039	-		.250	1.125
	10B12		7,8	-	-	43.771	-		.249	1.121
243	10B11	16	7	37.0	759	41.573	Bad Gage		.248	1.116
	10B15		7	-	-	43.429	-		.247	1.112
	10B17		7	-	-	40.987	-		.246	1.107
244	10B13	16	7,2,5,8	29.0	805	37.727	Comp. Fail		.220	.990
	10B14		7,2,5,8	-	-	36,688	-		.248	1.116
	10B16		2,5,8	..	-	35,613	-		.247	1.112
246	12.1	16	2,5,8	-	-	37.030	2450		.240	1.080
	12.2		2.5,8	-	-	45.970	-		.235	1.058
	12.3		2,5,8	-	-	45.628	-		.232	1.044
247	14.1	16	7	34.7	800	37.518	-	4.500	.233	1.049
	14.2		7	-	-	36.639	-		.233	1.049
	14.3		7	-	-	37.030	-		.233	1.049
248	10A1	18	7,8	NA	NA	43.867	-	5.000	.235	1.175
	10A3		7,8	-	-	44.113	-		.230	1.150
	10B5		7,8	-	-	45.579	-		.248	1.240
249	10A5	19	7	39.6	1760	43.918	-		.239	1.195
	10A6		7	-	-	49.194	-		.237	1.185
	10A7		7	-	-	48.315	-		.239	1.195
250	10A9	20	7	-	-	18.222	4470	1.500	.220	.330
	10B6		7	-	-	17.318	-		.249	.374
	10B8		7	-	-	17.611	-		.254	.381
251	10A10	21	7	16.2	830	16.488	4177		.230	.345
	10A13		7	-	-	17.440	-		.239	.344
	10A16		7	-	-	15.804	-		.232	.348
252	10A11	21	7	-	-	15.779	-		.231	.347
	10A14		7	-	-	15.730	-		.230	.345
	10A17		7	NA	NA	15.486	-		.232	.348
253	10A12	21	7	NA	NA	15.315	-		.231	.347
	10A15		7	-	-	14.802	-		.230	.345
	10A18		7	-	-	14.729	-		.235	.353

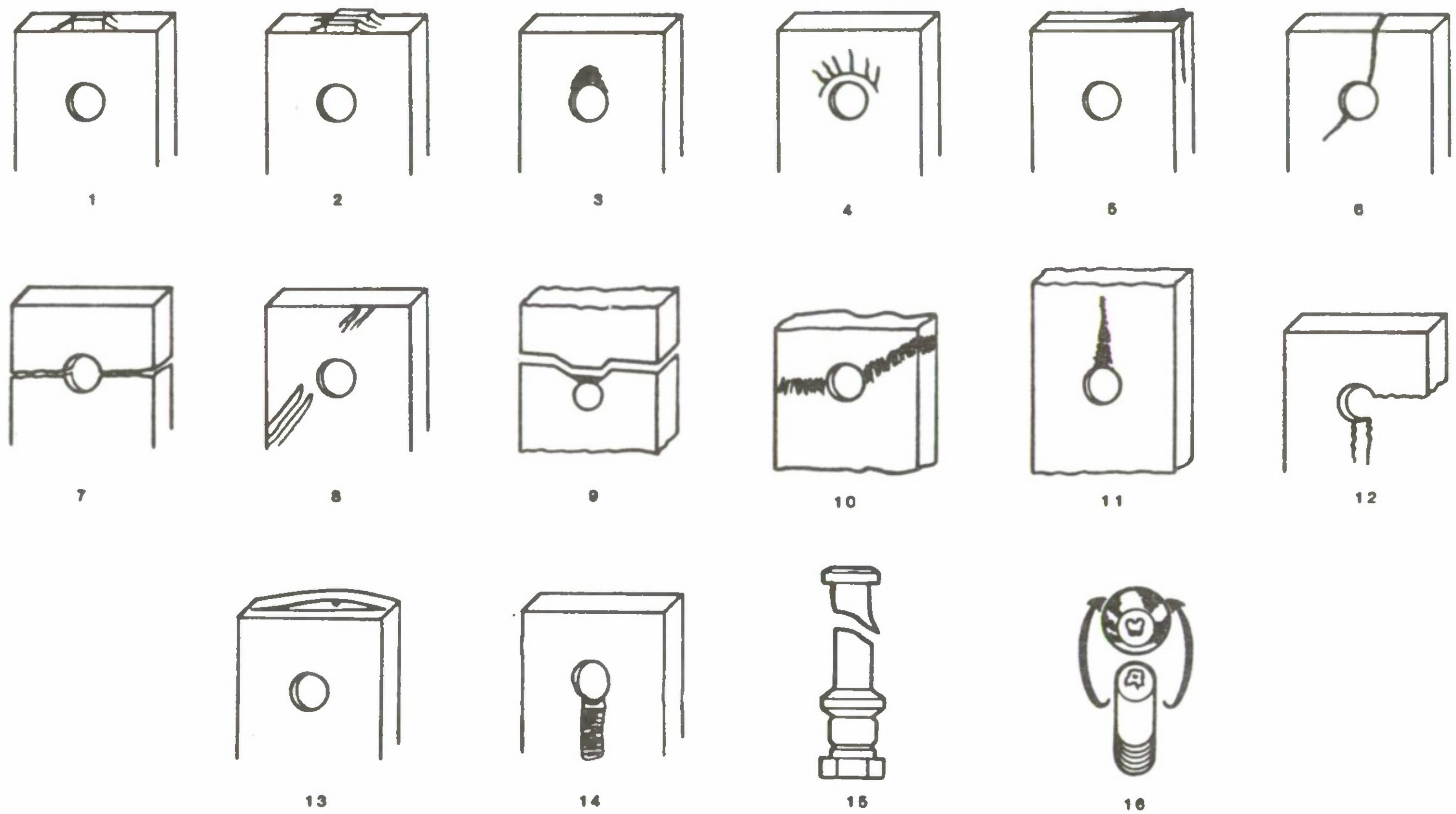
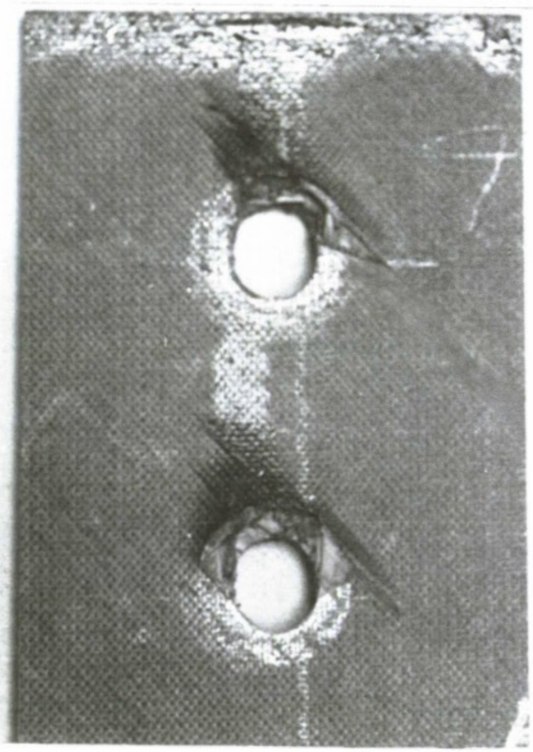
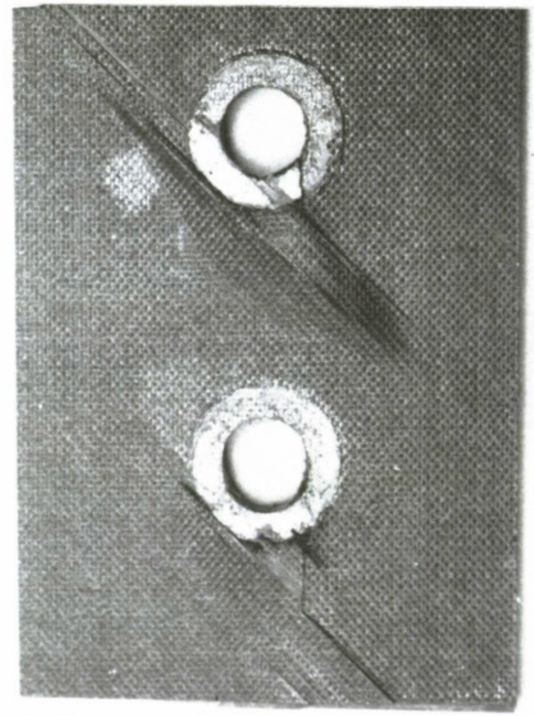


Figure 3-1. The Various Failure Modes and the Corresponding Mode Identification Numbers. (See Reference 1-2).



TC 201
SPEC 1A17



TC 201
SPEC 1A59

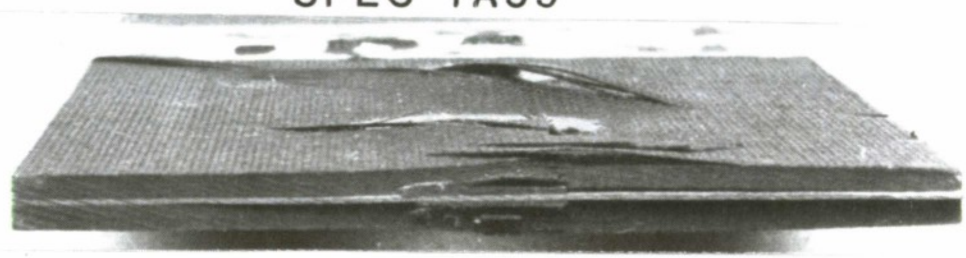
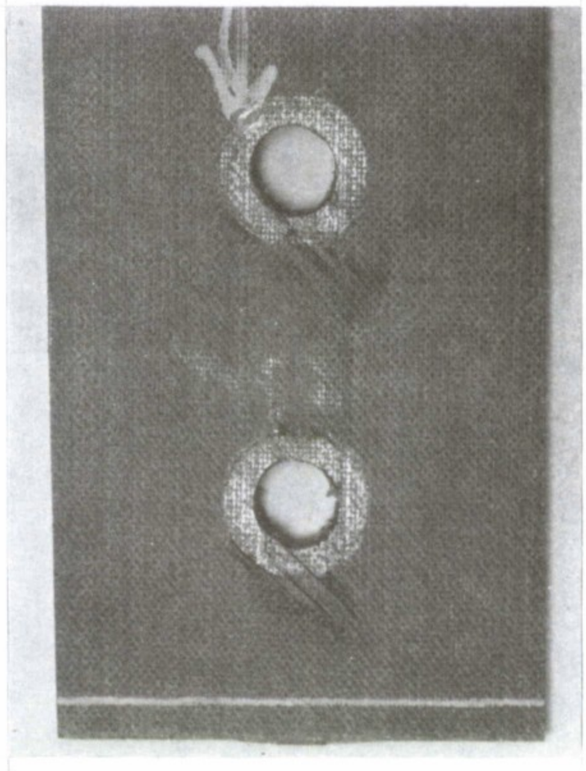


Figure 3-2. Failed Specimens from Test Case 201.



TC 202
SPEC 2.8

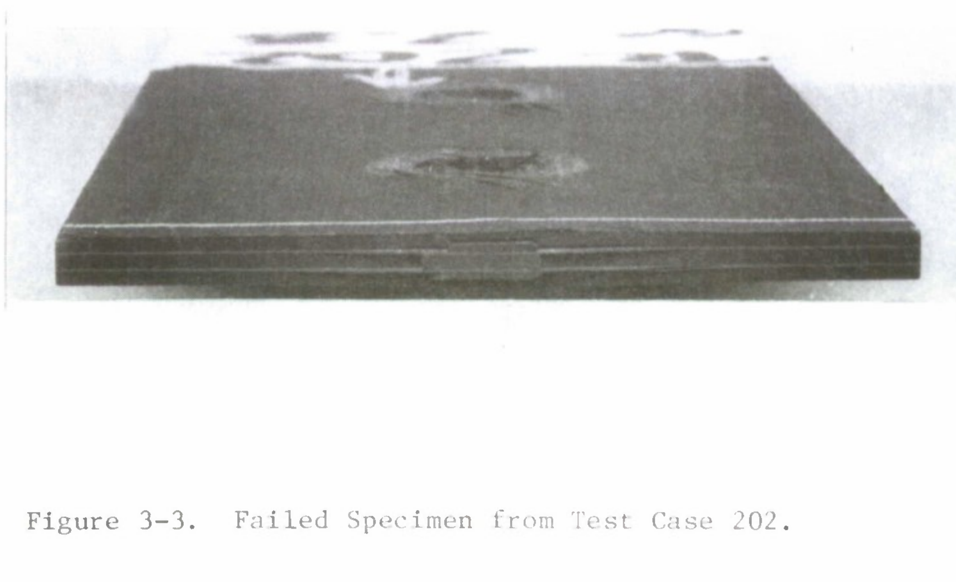
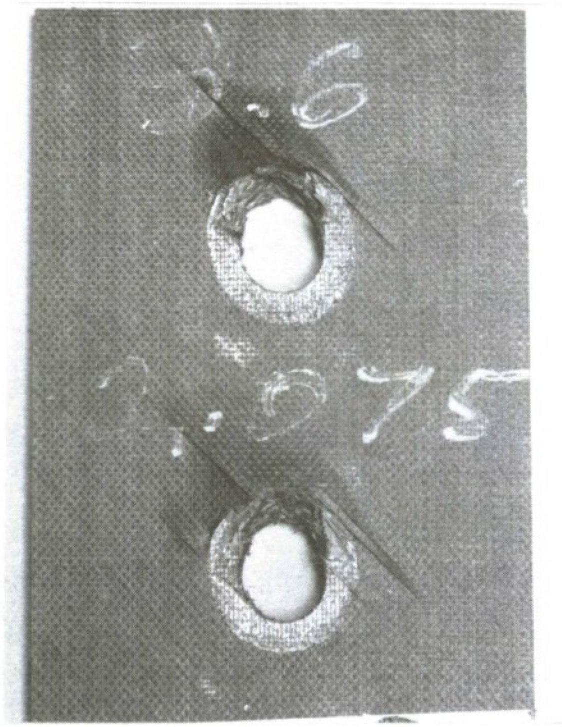


Figure 3-3. Failed Specimen from Test Case 202.



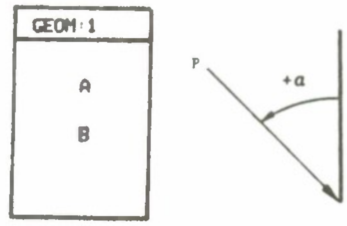
TC 203
SPEC 3.6

TC 203
SPEC 3.8

Figure 3-4. Failed Specimens from Test Case 203.

TEST CASE 201
SPECIMEN 1A17

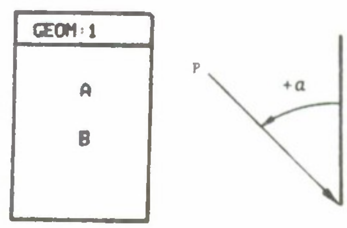
TOTAL SURVEY LOAD	=	3000.0	POUNDS
THE SUM OF THE AXIAL LOADS ON ALL BOLTS	=	2828.8	POUNDS
THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS	=	171.2	POUNDS
DIFFERENCE PER BOLT	=	85.6	POUNDS



HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	12	-1.79	-4.16	1399.9	-0.06
B	33	1.82	3.84	1429.8	1.99

TEST CASE 202
SPECIMEN 210

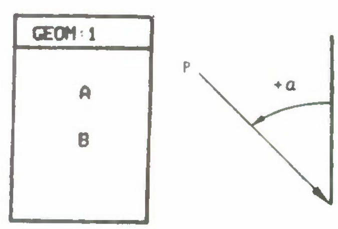
TOTAL SURVEY LOAD	=	3000.0	POUNDS
THE SUM OF THE AXIAL LOADS ON ALL BOLTS	=	2961.1	POUNDS
THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS	=	38.9	POUNDS
DIFFERENCE PER BOLT	=	19.5	POUNDS



HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	31	-3.89	0.72	1725.3	-4.05
B	32	-2.41	1.11	1242.4	3.51

TEST CASE 203
SPECIMEN 310

TOTAL SURVEY LOAD	=	3000.0	POUNDS
THE SUM OF THE AXIAL LOADS ON ALL BOLTS	=	2253.0	POUNDS
THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS	=	747.0	POUNDS
DIFFERENCE PER BOLT	=	373.5	POUNDS



HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	31	-1.84	1.11	1067.3	7.97
B	32	-2.31	1.09	1198.6	3.81

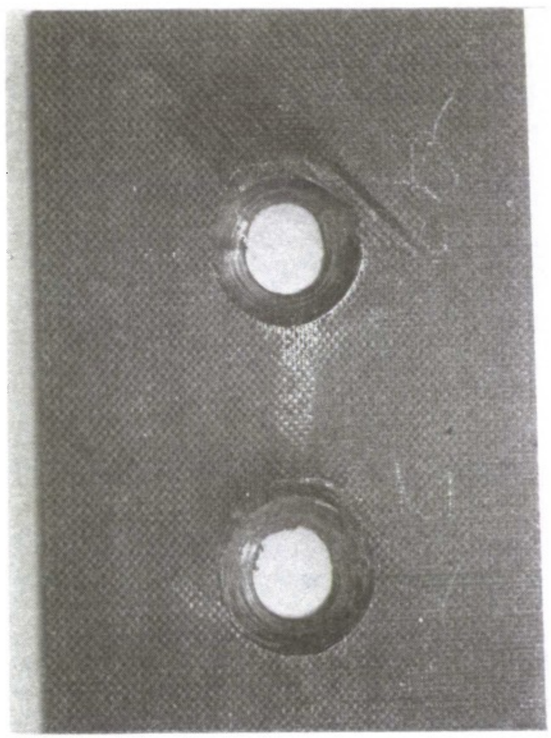
Figure 3-5. Fastener Load Measurements Using Strain-Gaged Bolts for Test Cases 201 to 203.

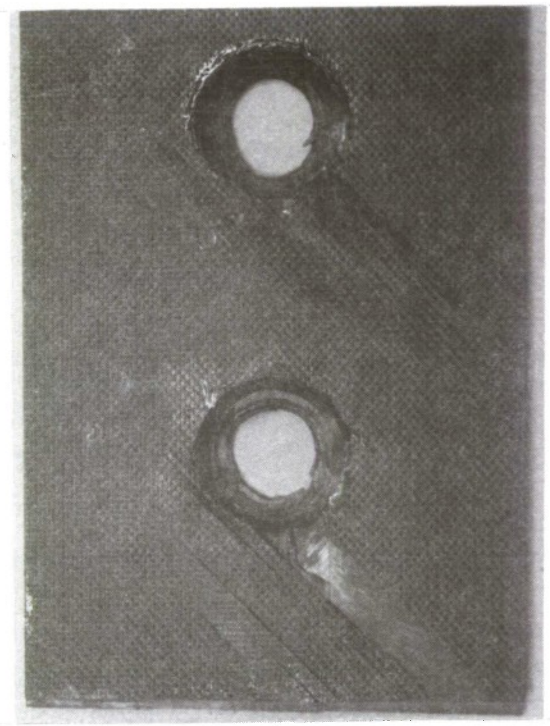
The effect of countersunk fasteners on the tensile strength of 50/40/10 laminates is addressed in test case 204. Table 3-1 indicates a failure load that is lower than realized with protruding head fasteners. The observed failure mode in this case was prediminantly a partial shear-out in two replicates and local bearing failure in one replicate (see Figure 3-6). Under static compression (test case 205), slightly larger failure loads were measured (Table 3-1), and the failure mode was predominantly a local bearing failure (see Figure 3-7). The two fasteners were estimated to divide the load nearly equally, using strain-gaged bolts (see Figure 3-8).

In a double shear tensile load transfer configuration, the 50/40/10 laminate suffered a net section or cleavage failure, in contrast to the bearing or partial shear-out failure observed in a single shear situation (compare test cases 201 and 206, and Figures 3-2 and 3-9). When the double shear load transfer was effected under ETW (218^{o}F, wet) conditions, the failure mode switched to the local bearing mode (compare test cases 206 and 207 in Table 3-1, and Figures 3-9 and 3-10).

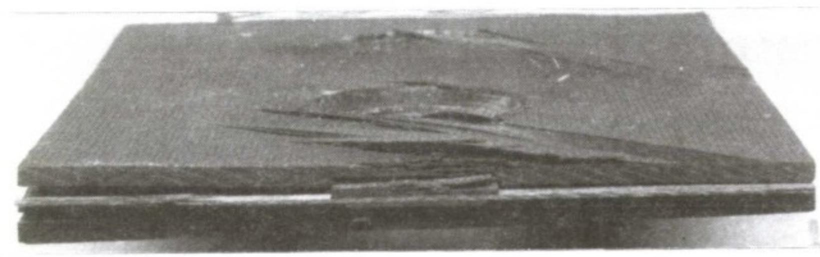
In a single shear load transfer configuration, tensile tests under ETW conditions (test case 208) produced lower failure loads (see Table 3-1) compared to RTD test results (test case 201). As in most of the RTD test specimens, ETW failure was induced by local bearing (see Figure 3-10). In contrast, under compressive loading (test case 209), the ETW test specimens exhibited a net section failure mode (see Figure 3-11).

Unless otherwise specified, all the tests were conducted after torquing the fasteners to 100 in-lbs. In test cases 210 and 211, the fastener torque was changed to 0 (finger-tight) and 200 in-lbs, respectively. Under a tensile load, the laminate with finger tight fasteners failed in a partial shear-out mode (see Figure 3-12). At a fastener torque value of 200 in-lbs, one replicate exhibited a net section mode of failure, and three others failed in a partial shear-out mode (see Figures 3-12 and 3-13). The failure load increased with the fastener torque value (compare test case 210, 201 and 211 in Table 3-1). Fastener load measurements using strain-gaged bolts again indicate an approximately equal division of the applied load between the two fasteners (Figure 3-14).



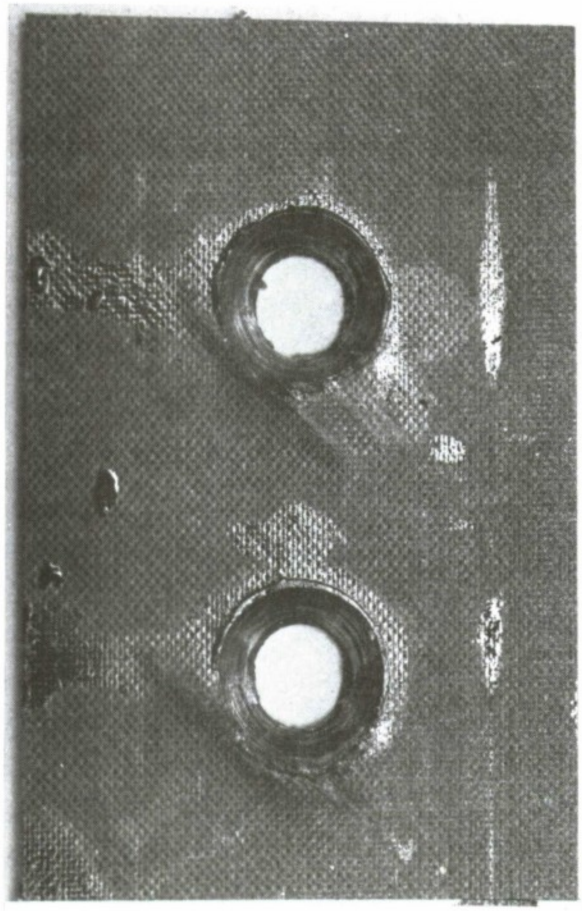


TC 204
SPEC 1A60



TC 204
SPEC 1A45

Figure 3-6. Failed Specimens from Test Case 204.



TC 205
SPEC 1A46

Figure 3-7. Failed Specimen from Test Case 205.

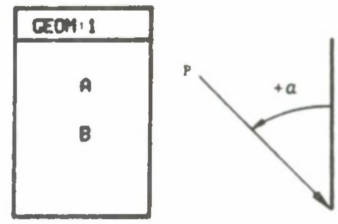
TEST CASE 204
SPECIMEN 1A30

TOTAL SURVEY LOAD = 3000.0 POUNDS

THE SUM OF THE AXIAL LOADS ON ALL BOLTS = 2825.5 POUNDS

THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS = 174.5 POUNDS

DIFFERENCE PER BOLT = 87.3 POUNDS



HOLE	BOLT ID	230 DEG.	280 DEG.	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
		(VOLTS)			
A	C33	1.21	2.69	1317.8	2.17
B	C11	-2.47	0.29	1508.7	-0.85

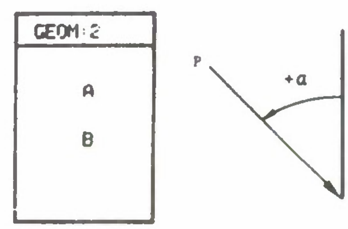
TEST CASE 206
SPECIMEN 1A15

TOTAL SURVEY LOAD = 5000.0 POUNDS

THE SUM OF THE AXIAL LOADS ON ALL BOLTS = 4436.7 POUNDS

THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS = 563.3 POUNDS

DIFFERENCE PER BOLT = 281.7 POUNDS



HOLE	BOLT ID	230 DEG.	280 DEG.	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
		(VOLTS)			
A	D34	1.77	-1.32	2181.2	4.18
B	D37	1.74	-0.32	2262.1	1.52

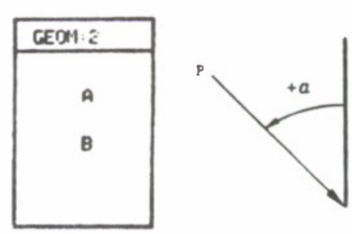
TEST CASE 207
SPECIMEN 1A48

TOTAL SURVEY LOAD = 5000.0 POUNDS

THE SUM OF THE AXIAL LOADS ON ALL BOLTS = 3275.9 POUNDS

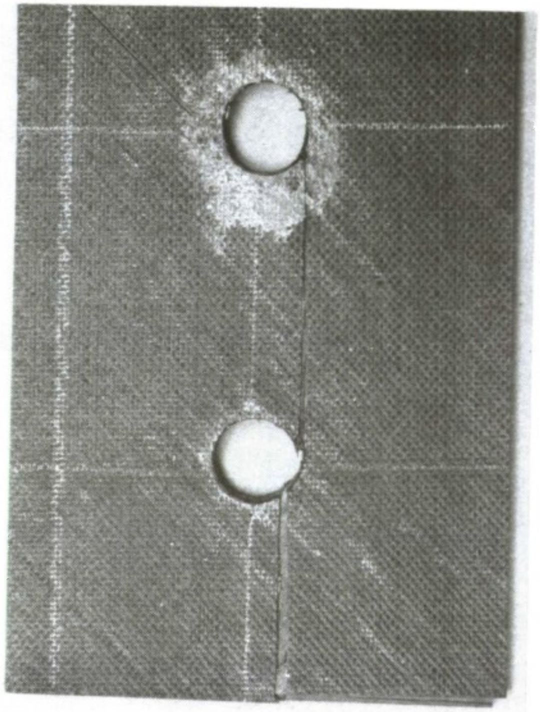
THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS = 1724.1 POUNDS

DIFFERENCE PER BOLT = 862.0 POUNDS

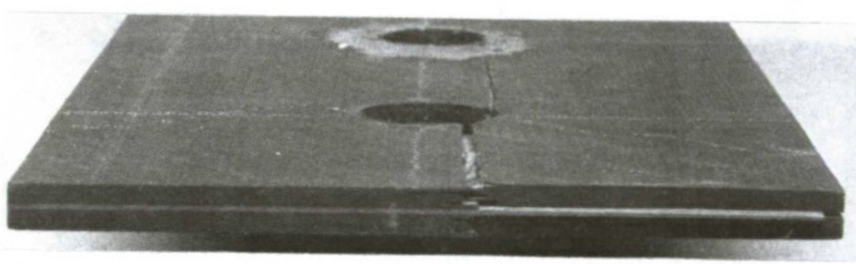


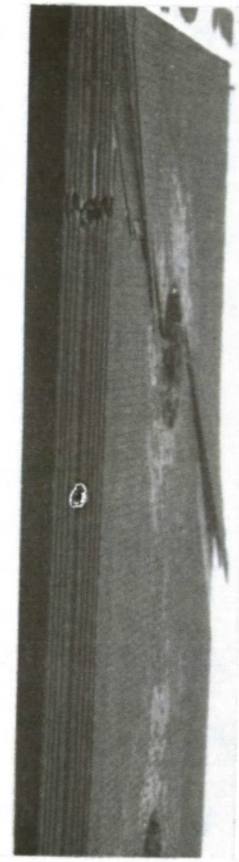
HOLE	BOLT ID	230 DEG.	280 DEG.	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
		(VOLTS)			
A	D34	1.56	-0.94	1805.5	1.24
B	D36	1.31	-0.36	1470.9	0.19

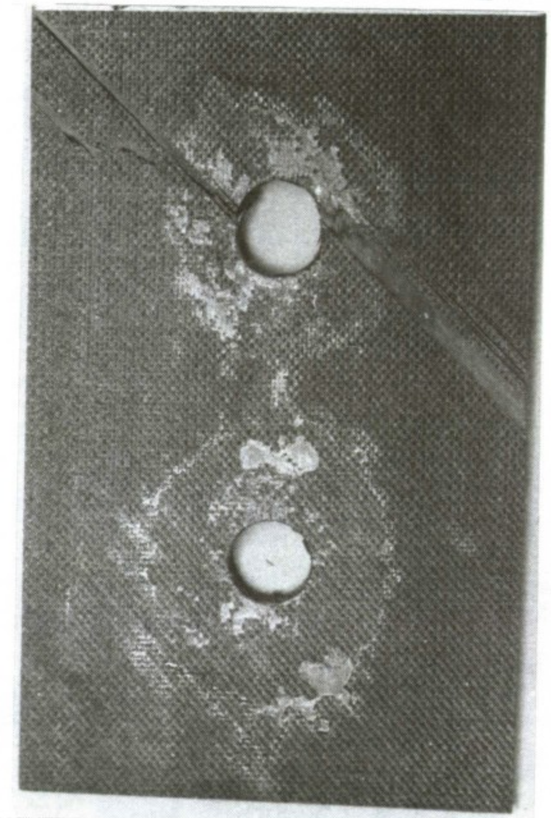
Figure 3-8. Fastener Load Measurements Using Strain-Gaged Bolts for Test Cases 205 to 207.



TC 206
SPEC 1A15

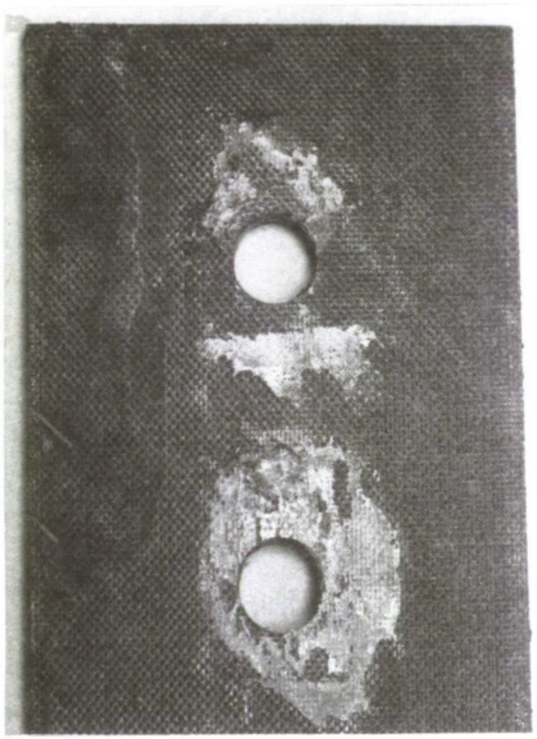




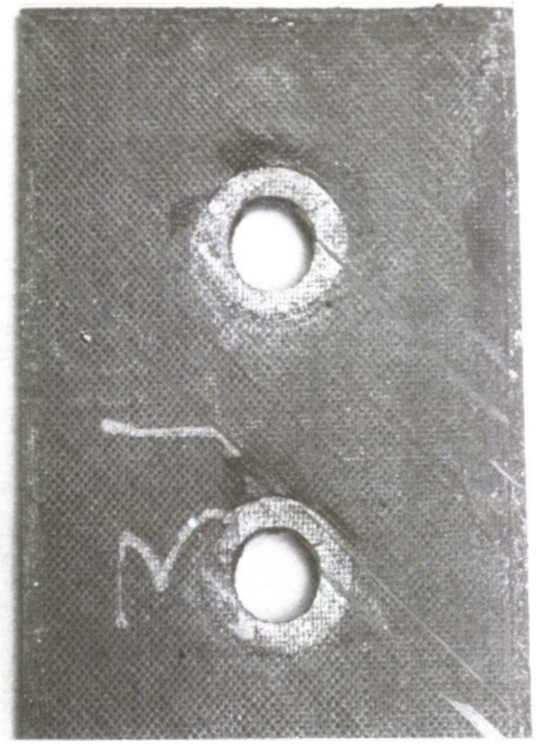


TC 206
SPEC 1A47

Figure 3-9. Failed Specimens from Test Case 206

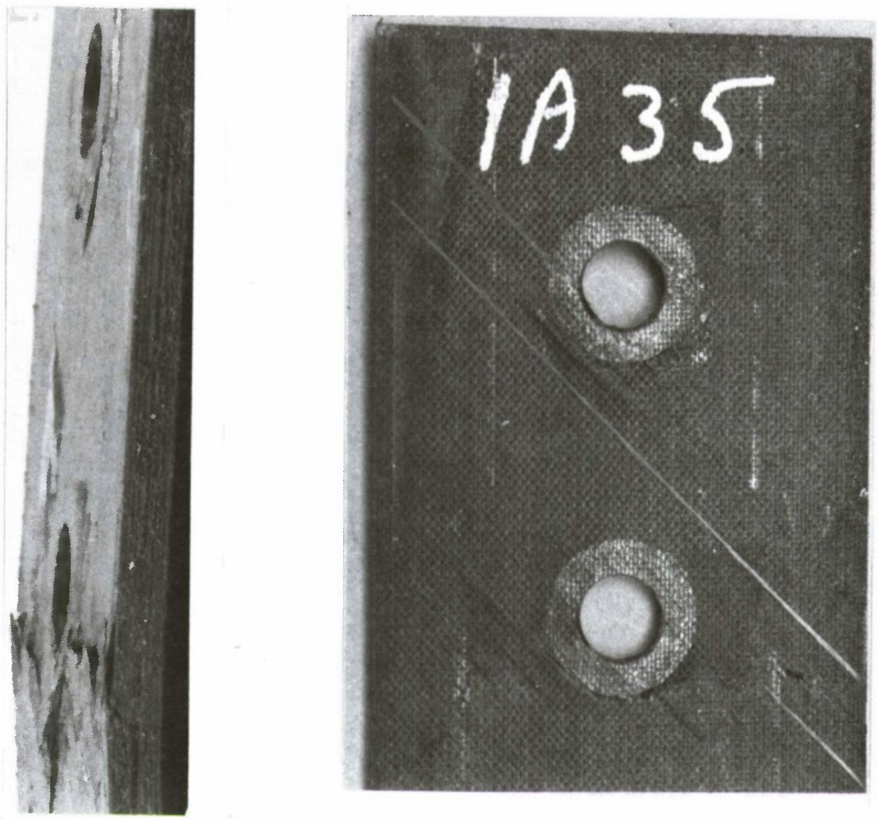


TC 207
SPEC 1A33



TC 208
SPEC 1A64

Figure 3-10. Failed Specimens from Test Cases 207 and 208.



TC 209
SPEC 1A35

Figure 3-11. Failed Specimen from Test Case 209.

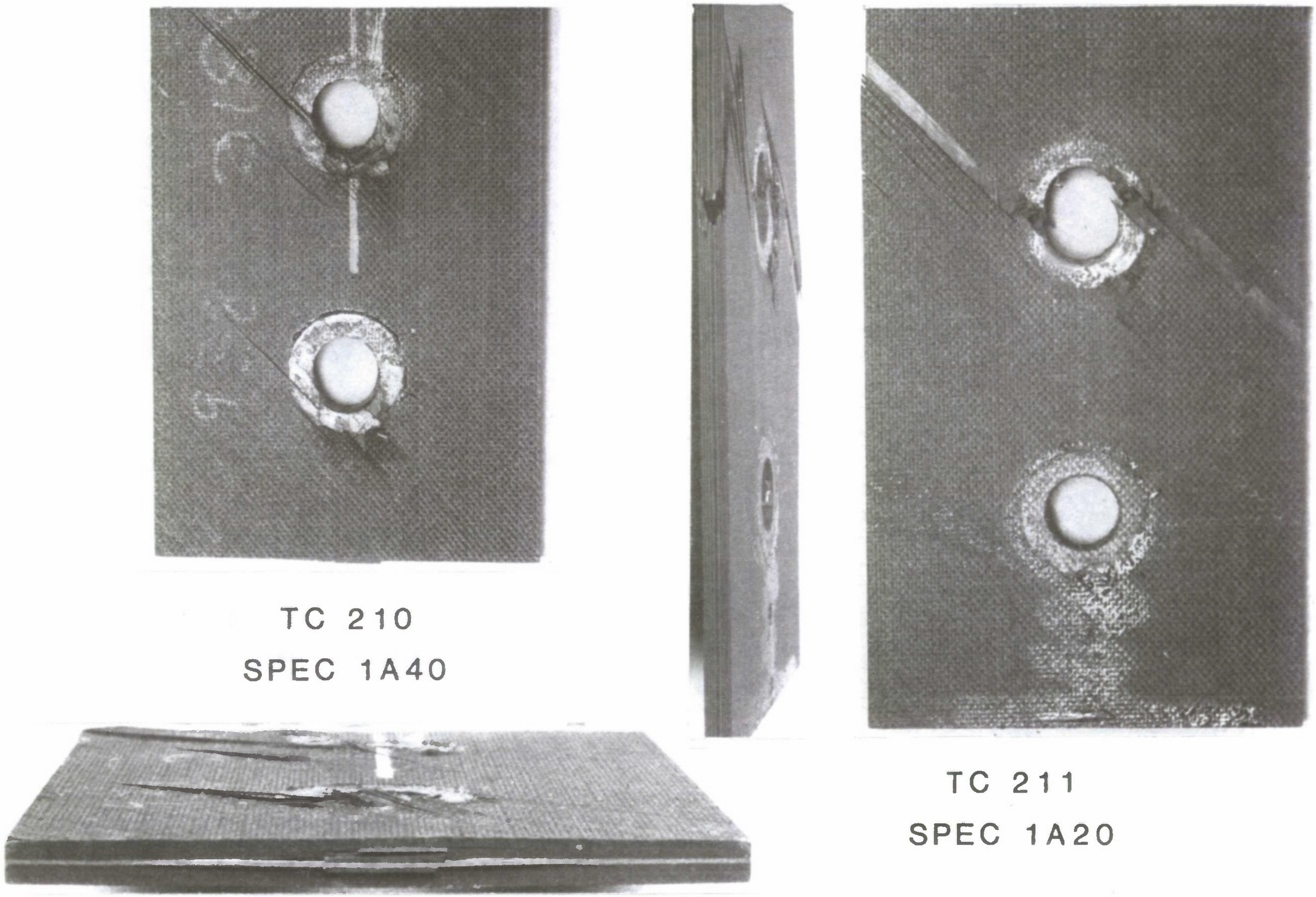
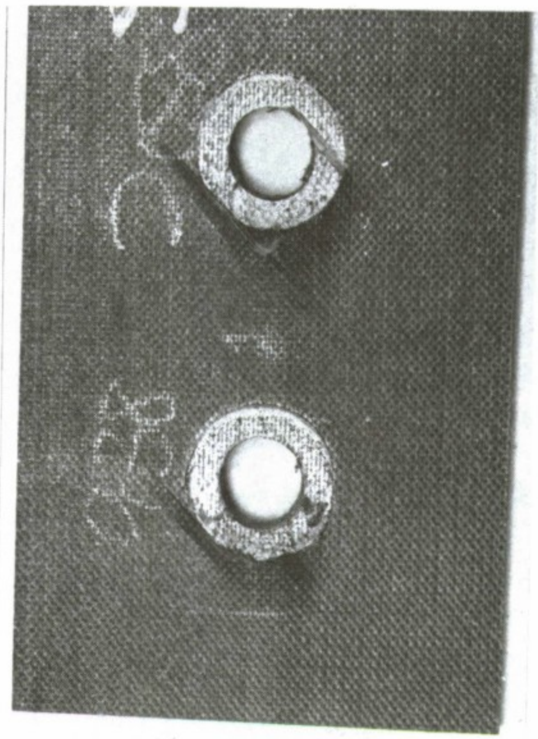


Figure 3-12. Failed Specimens from Test Cases 210 and 211.



TC 211
SPEC 1A56

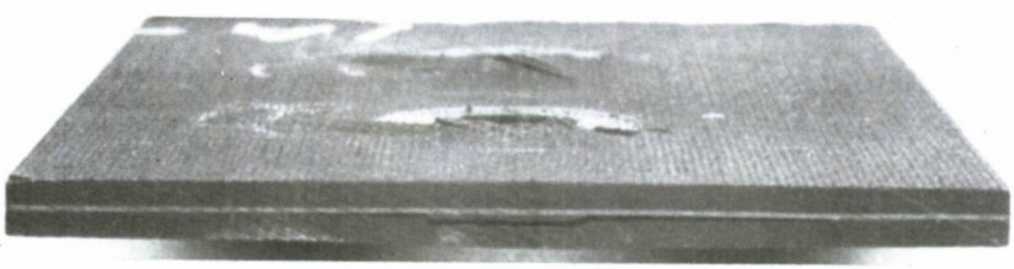
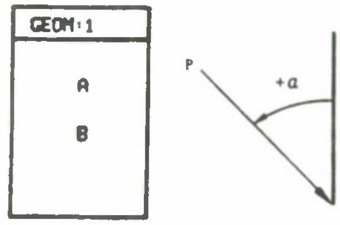


Figure 3-13. A Different Failure Mode Observed in Test Case 211.

TEST CASE 208
SPECIMEN 1A49

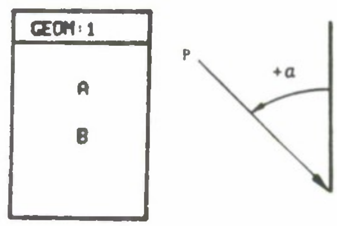
TOTAL SURVEY LOAD	= 3000.0	POUNDS
THE SUM OF THE AXIAL LOADS ON ALL BOLTS	= 3115.8	POUNDS
THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS	= -115.8	POUNDS
DIFFERENCE PER BOLT	= -57.9	POUNDS



HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	11	-3.34	1.07	1667.1	5.51
B	12	-1.63	-4.27	1458.2	-2.86

TEST CASE 210
SPECIMEN 1A59

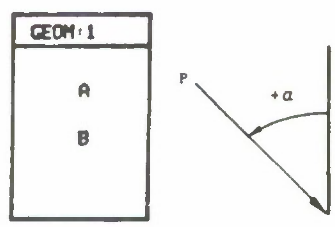
TOTAL SURVEY LOAD	= 3000.0	POUNDS
THE SUM OF THE AXIAL LOADS ON ALL BOLTS	= 2489.7	POUNDS
THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS	= 510.3	POUNDS
DIFFERENCE PER BOLT	= 255.1	POUNDS



HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	31	-2.76	0.81	1310.9	-0.34
B	32	-2.36	0.96	1179.6	2.06

TEST CASE 211
SPECIMEN 1A20

TOTAL SURVEY LOAD	= 3000.0	POUNDS
THE SUM OF THE AXIAL LOADS ON ALL BOLTS	= 1856.7	POUNDS
THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS	= 1143.3	POUNDS
DIFFERENCE PER BOLT	= 571.7	POUNDS



HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	12	-1.31	-2.55	838.5	5.19
B	33	1.45	2.79	1025.9	5.18

Figure 3-14. Fastener Load Measurement Using Strain-Gaged Bolts for Test Cases 208, 210 and 211.

In Test cases 212 and 213, the fastener spacing (S_L) was reduced from four hole diameters (4D) to 3D and 2D, respectively. The closer the fasteners were brought together, the lower was the failure load (see Table 3-1, test cases 201, 212 and 213). Also the change in the fastener spacing, from 4D to 3D or 2D, caused the failure mode to switch from local bearing to cleavage mode accompanied by delaminations (see Figures 3-15 and 3-16).

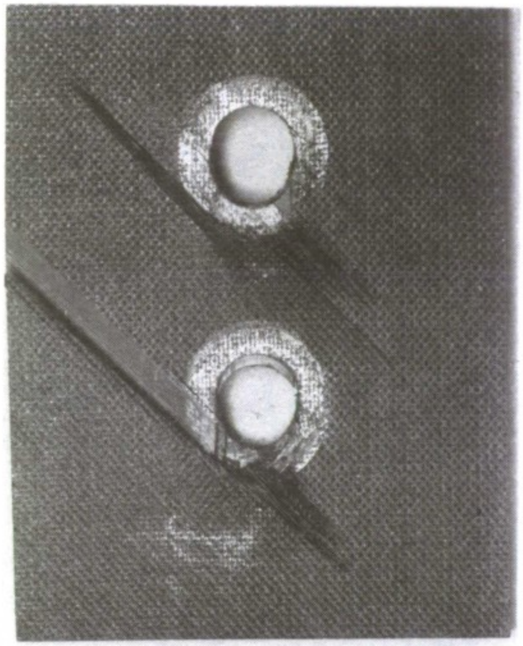
Test case 213 was conducted on 50/40/10 laminates under a single shear tensile load transfer situation, using closely spaced (2D) 5/16 inch diameter protruding head steel fasteners. In a similar situation, 30/60/10 laminates exhibited the local bearing mode of failure exhibited by 50/40/10 laminates, while 70/20/10 laminates exhibited a partial shear-out mode of failure (see Figures 3-17 and 3-18). The fastener loads for these test cases (214 and 215), are presented in Figures 3-19 and 3-20.

3.2 Results from Tests on Joints with Two Fasteners at an Angle to the Load Distribution

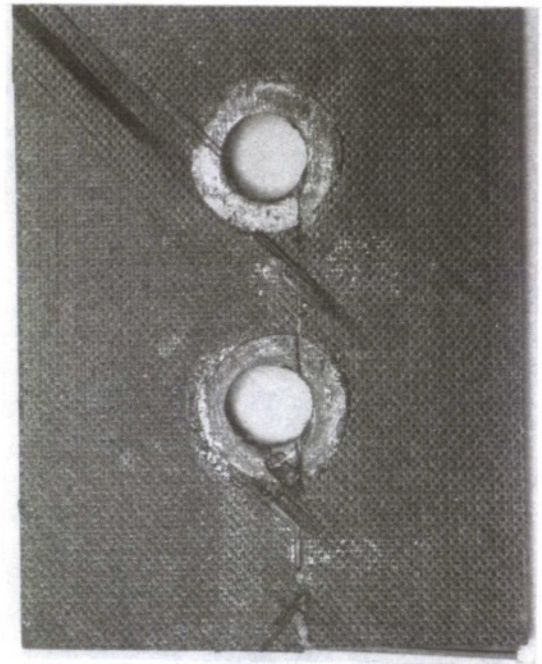
Test cases 216 to 224 (see Table 2-1) considered joints with two fasteners at an angle to the load direction. The fastener spacing in the loading and transverse directions (S_L and S_T, respectively) was varied. The loading configuration was changed from single to double shear. Tests were conducted under RTD and ETW conditions. Protruding head and 100° countersunk steel fasteners were used, and three laminate layups (50/40/10, 70/20/10 and 30/60/10) were tested.

A tensile load on 50/40/10 laminates, in a single shear configuration, precipitated cleavage and partial shear-out failures (Figure 3-21). In a double shear configuration, a cleavage failure was observed under RTD and ETW conditions (Figures 3-22 and 3-23). A compressive load under a double shear configuration produced a net section compressive failure (Figure 3-24).

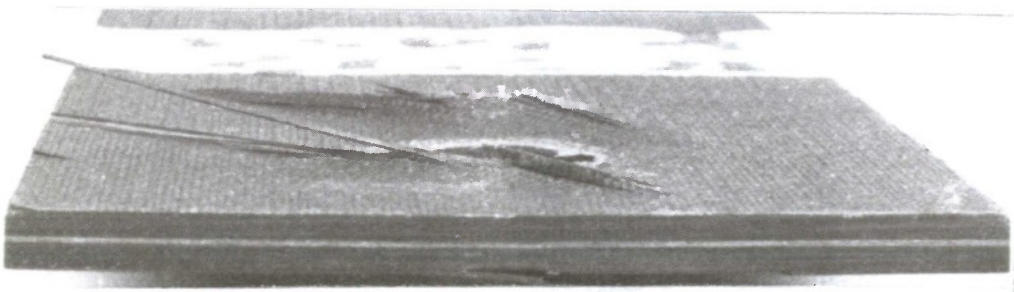
When the fastener spacing was increased from 2D to 3D or 4D (test cases 220 and 221), a larger tensile failure load was measured in a single shear configuration. This corresponded to local bearing and partial shear-out failures (Figures 3-24 and 3-25).



TC 212
SPEC 1A53



TC 212
SPEC 1A68



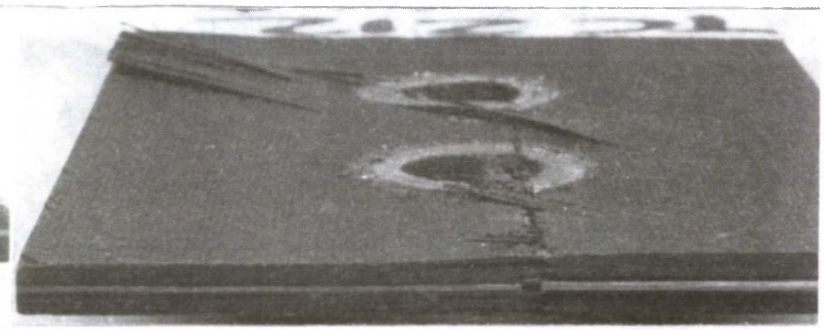
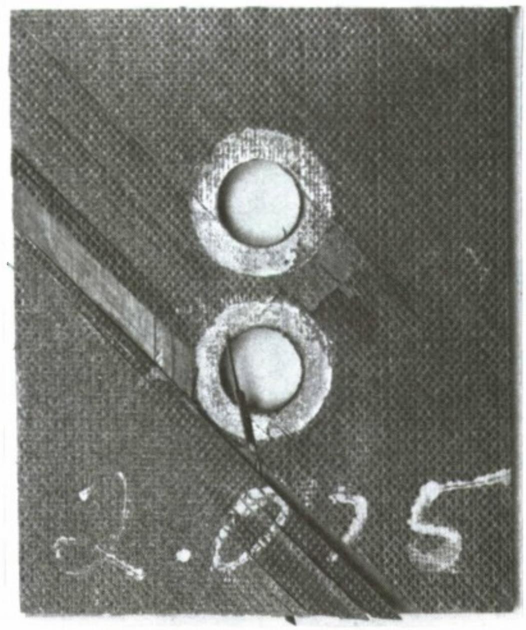
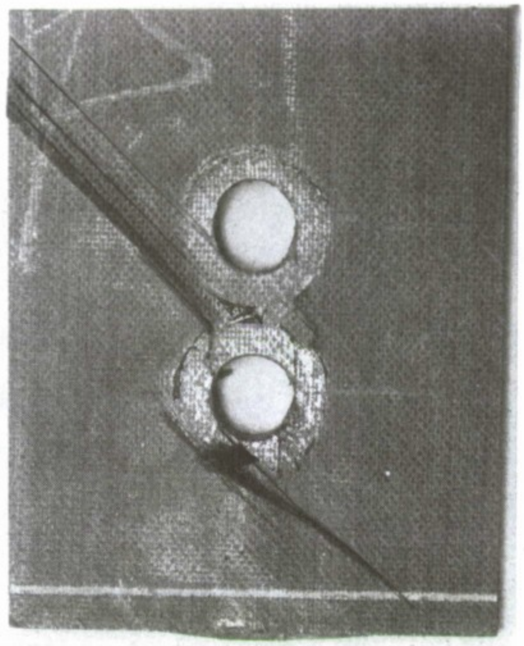


Figure 3-15. Failed Specimens from Test Case 212.



TC 213
SPEC 1A39

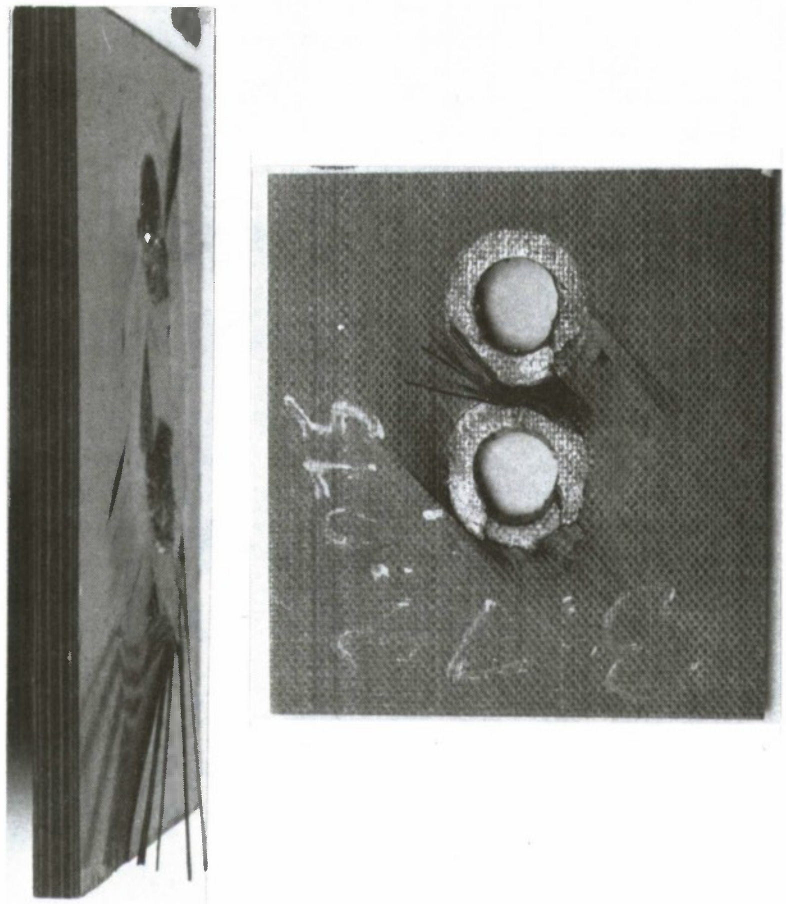
Figure 3-16. Failed Specimen from Test Case 213.



TC 214

SPEC 2.9

Figure 3-17. Failed Specimen from Test Case 214.



TC 215
SPEC 3.7

Figure 3-18. Failed Specimen from Test Case 215.

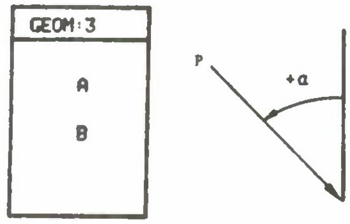
TEST CASE 212
SPECIMEN 1A68

TOTAL SURVEY LOAD = 3000.0 POUNDS

THE SUM OF THE AXIAL
LOADS ON ALL BOLTS = 2525.6 POUNDS

THE DIFFERENCE BETWEEN
THE BOLT SURVEY LOAD AND
THE SUM OF THE AXIAL LOADS = 474.4 POUNDS

DIFFERENCE PER BOLT = 237.2 POUNDS



HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	31	-2.68	0.78	1270.9	-0.42
B	32	-2.47	1.08	1256.3	2.89

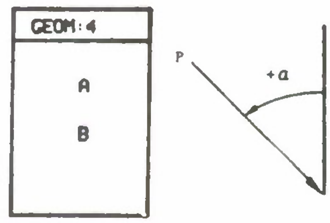
TEST CASE 213
SPECIMEN 1A69

TOTAL SURVEY LOAD = 3000.0 POUNDS

THE SUM OF THE AXIAL
LOADS ON ALL BOLTS = 2396.2 POUNDS

THE DIFFERENCE BETWEEN
THE BOLT SURVEY LOAD AND
THE SUM OF THE AXIAL LOADS = 603.8 POUNDS

DIFFERENCE PER BOLT = 301.9 POUNDS



HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	31	-2.56	1.02	1301.4	2.83
B	32	-2.19	0.90	1097.3	2.18

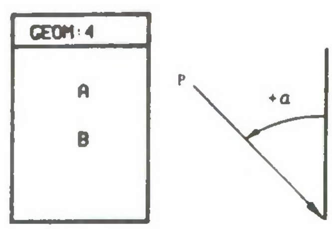
TEST CASE 214
SPECIMEN 211

TOTAL SURVEY LOAD = 3000.0 POUNDS

THE SUM OF THE AXIAL
LOADS ON ALL BOLTS = 2734.2 POUNDS

THE DIFFERENCE BETWEEN
THE BOLT SURVEY LOAD AND
THE SUM OF THE AXIAL LOADS = 265.8 POUNDS

DIFFERENCE PER BOLT = 132.9 POUNDS

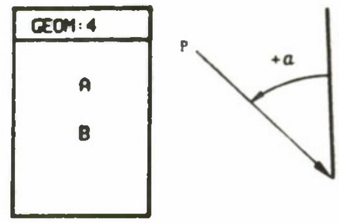


HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	31	-3.16	0.84	1474.5	-1.24
B	32	-2.44	1.14	1262.7	3.69

Figure 3-19. Fastener Load Measurements Using Strain-Gaged Bolts for Test Cases 212 to 214.

TEST CASE 215
SPECIMEN 311

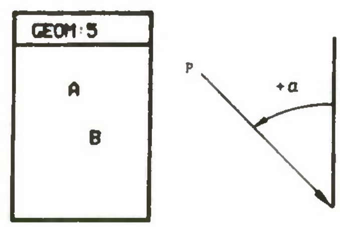
TOTAL SURVEY LOAD	=	3000.0	POUNDS
THE SUM OF THE AXIAL LOADS ON ALL BOLTS	=	2856.7	POUNDS
THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS	=	143.3	POUNDS
DIFFERENCE PER BOLT	=	71.6	POUNDS



HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	31	-3.31	0.89	1547.5	-1.14
B	32	-2.38	1.39	1318.1	6.55

TEST CASE 216
SPECIMEN 1B23

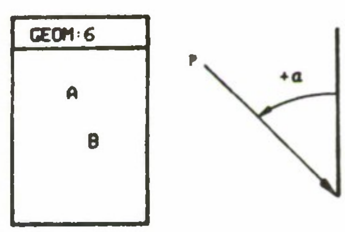
TOTAL SURVEY LOAD	=	3000.0	POUNDS
THE SUM OF THE AXIAL LOADS ON ALL BOLTS	=	2560.8	POUNDS
THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS	=	439.2	POUNDS
DIFFERENCE PER BOLT	=	219.6	POUNDS



HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	31	-3.07	0.57	1362.1	-4.03
B	32	-2.15	1.32	1211.6	7.22

TEST CASE 217
SPECIMEN 1B27

TOTAL SURVEY LOAD	=	5000.0	POUNDS
THE SUM OF THE AXIAL LOADS ON ALL BOLTS	=	5538.4	POUNDS
THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS	=	-538.4	POUNDS
DIFFERENCE PER BOLT	=	-269.2	POUNDS



HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	D35	1.91	-0.93	2433.3	-9.47
B	D37	2.14	-1.31	3187.2	10.05

Figure 3-20. Fastener Load Measurements Using Strain-Gaged Bolts for Test Cases 215 to 217.

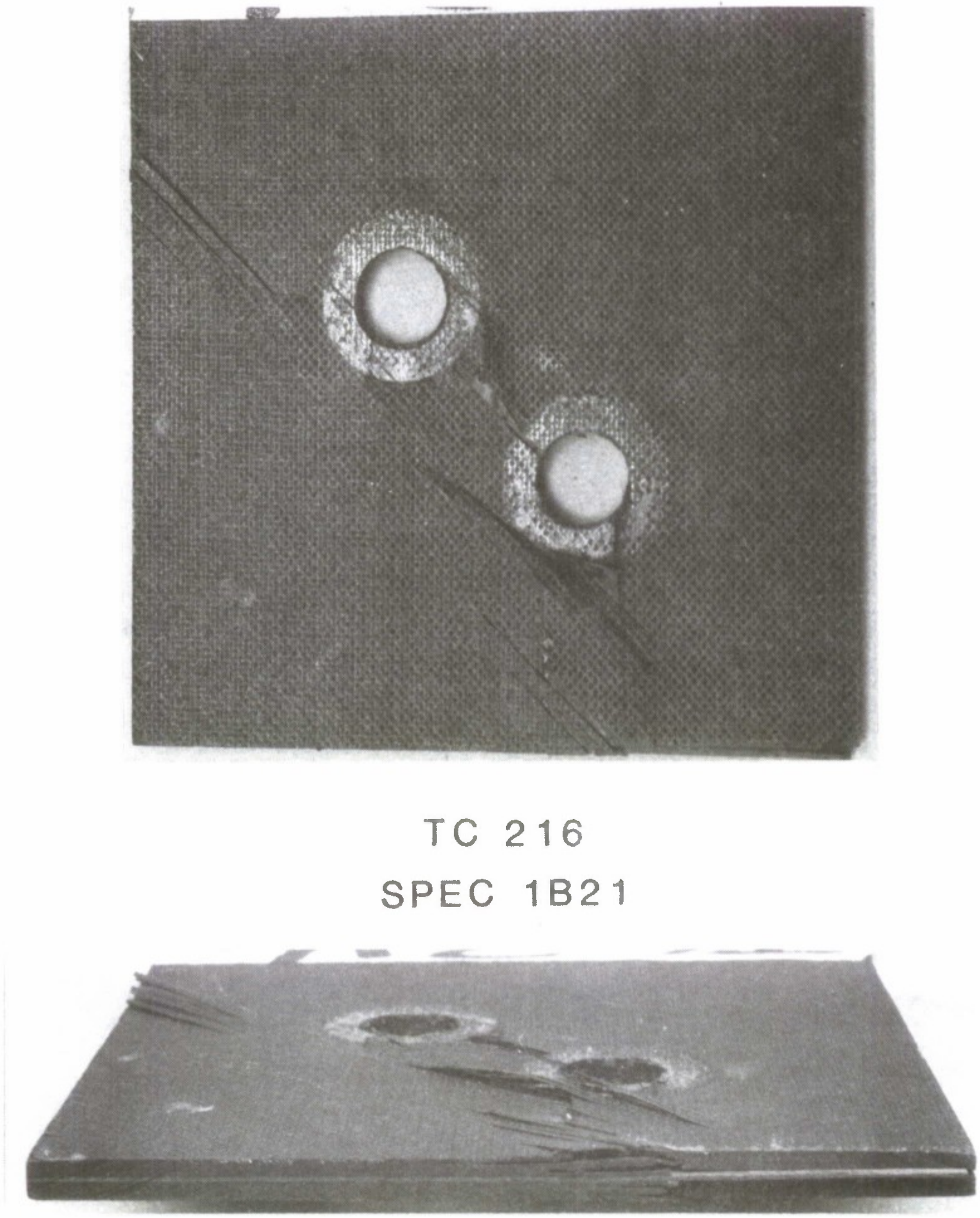
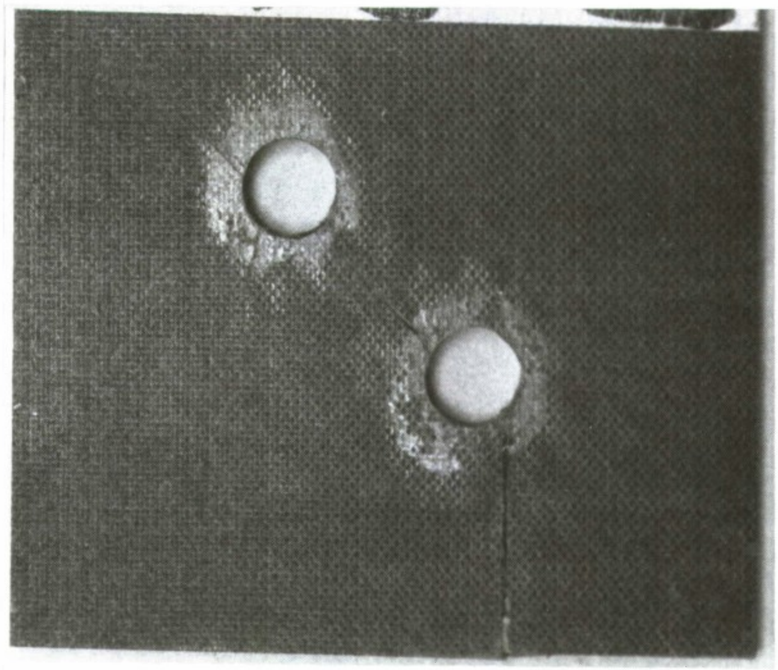


Figure 3-21. Failed Specimen from Test Case 216.



TC 217

SPEC 1B29

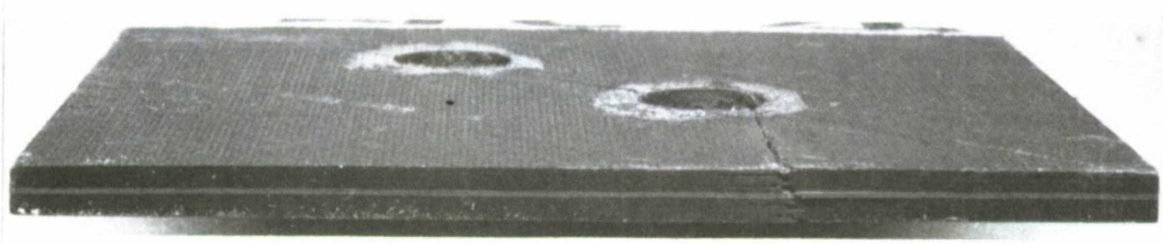
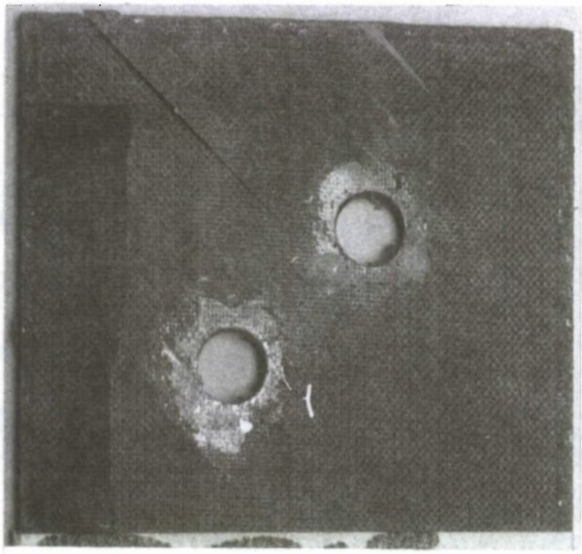
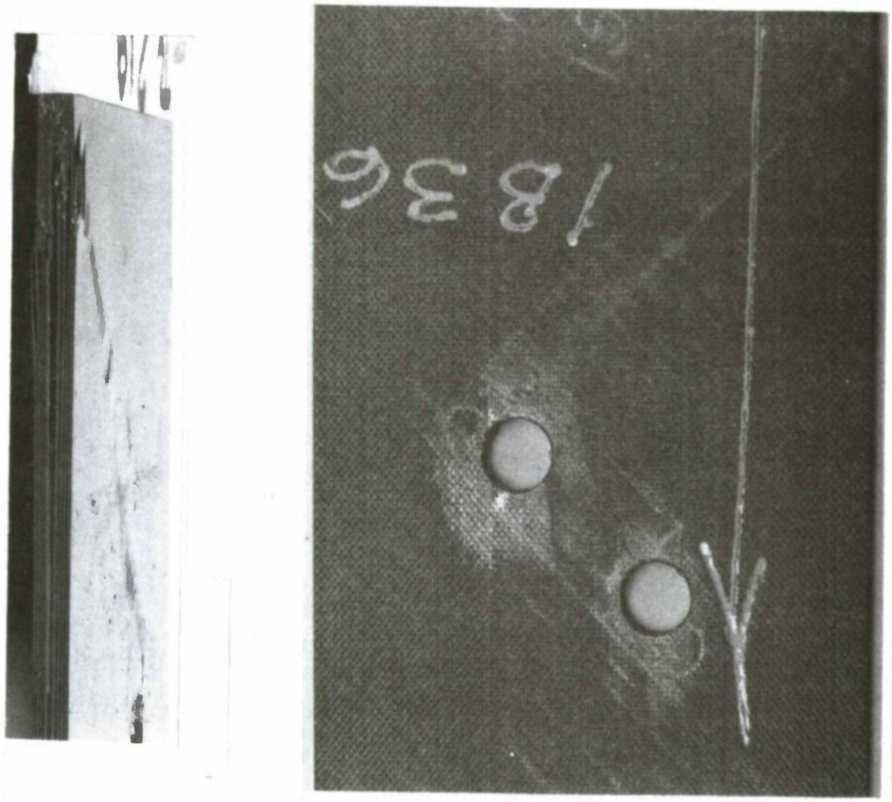


Figure 3-22. Failed Specimen from Test Case 217.

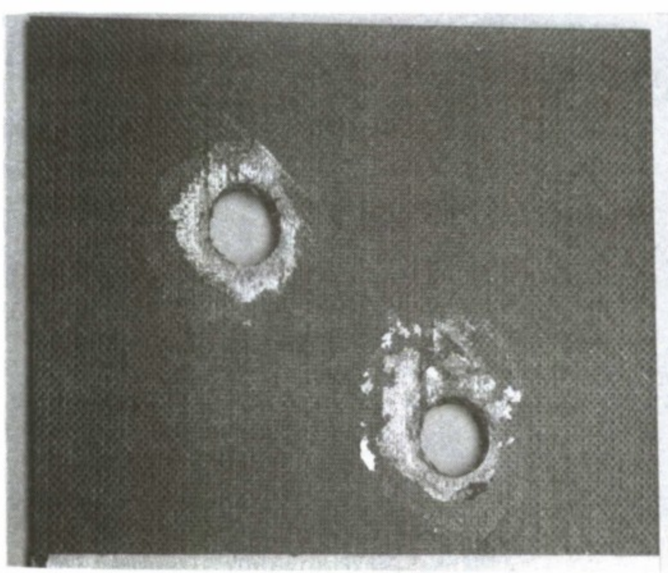


TC 218
SPEC 1B39

Figure 3-23. Failed Specimen from Test Case 218.



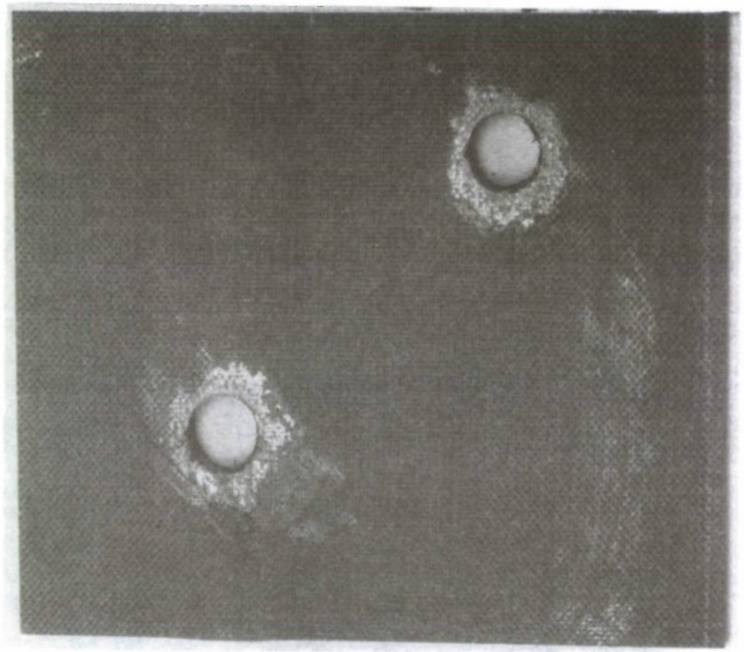
TC 219
SPEC 1B36



TC 220
SPEC 1D6

Figure 3-24. Failed Specimens from Test Cases 219 and 220.

TC 221
SPEC 1D3



TC 221
SPEC 1D1

Figure 3-25. Failed Specimens from Test Case 221.

When protruding head fasteners were replaced by 100° countersunk fasteners, a cleavage mode of failure was observed without any shear-out indication (Figure 3-26).

In a double shear tensile load transfer configuration, with closely spaced ($S_L = S_T = 2D$) 5/16 inch diameter protruding head steel fasteners, 70/20/10 laminates failed in a partial shear-out mode (Figure 3-27). Under the same conditions, 30/60/10 laminates exhibited a cleavage failure mode (Figure 3-28).

When two fasteners are at an angle to the loading direction, and are located near each other (S_T, $S_L = 4$), their stress concentration effects interact, and are additive. Also, the fastener loads contain contributions in the transverse direction that increase when S_L is decreased. Figures 3-20, 3-29, 3-30 and 3-31 present fastener load values computed based on strain-gaged bolt measurements.

3.3 Results from Tests on Joints with Four Fasteners in a Rectangular Pattern

Test cases 225 to 232 in Table 2-1 address tests on joints with four fasteners in a rectangular pattern. As in the case of other fastener arrangements, fastener spacing, load eccentricity (single versus double shear), type of load (tensile versus compressive), fastener geometry and test environment are varied. Results from these tests are presented in Table 3-1.

Failed specimens from each of the referenced test cases are presented in Figures 3-32 to 3-39. The failure modes are similar to those observed under similar conditions with two fasteners in tandem.

The load distribution among the four fasteners, for the considered test cases, were computed based on strain-gaged bolt measurements. These distributions are presented in Figures 3-31, 3-40 and 3-41. A comparison of these results with the sample failed specimen photographs should determine if a correlation exists between the failure initiation fastener location and the location corresponding to the maximum fastener load.

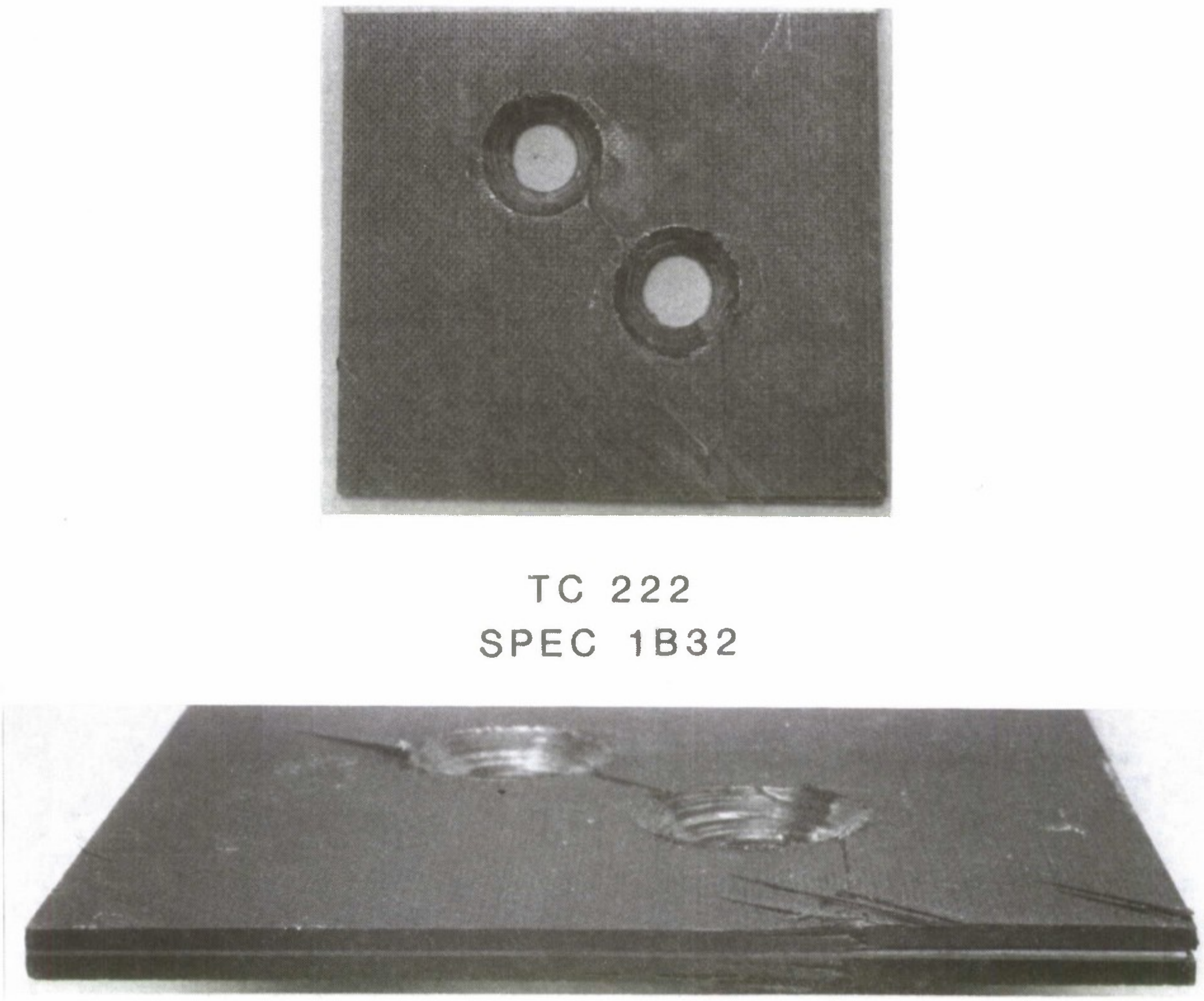
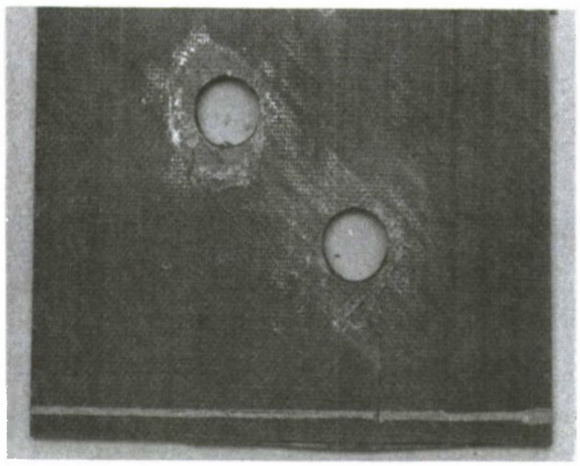


Figure 3-26. Failed Specimen from Test Case 222.



TC 223

SPEC 214

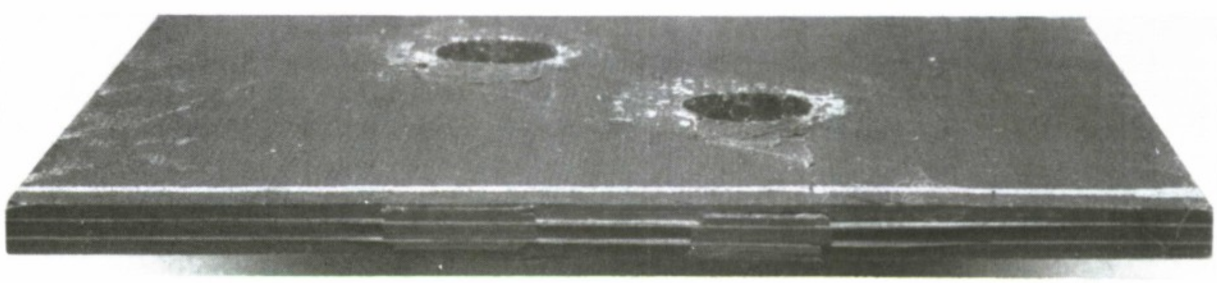
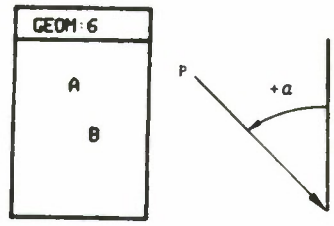


Figure 3-27. Failed Specimen from Test Case 223.

Figure 3-28. Failed Specimen from Test Case 224.

TEST CASE 218
SPECIMEN 1B39

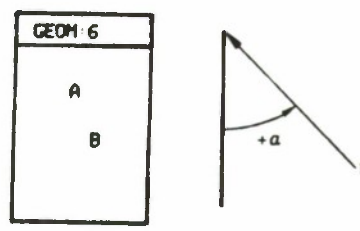
TOTAL SURVEY LOAD	=	5000.0 POUNDS
THE SUM OF THE AXIAL LOADS ON ALL BOLTS	=	4736.8 POUNDS
THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS	=	263.2 POUNDS
DIFFERENCE PER BOLT	=	131.6 POUNDS



HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	D36	2.37	-0.68	2676.2	0.53
B	D37	1.47	-0.64	2075.6	6.87

TEST CASE 219
SPECIMEN 1B36

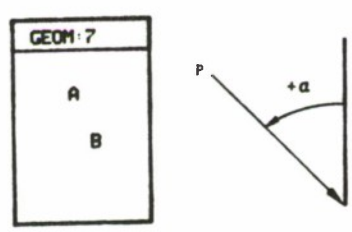
TOTAL SURVEY LOAD	=	5000.0 POUNDS
THE SUM OF THE AXIAL LOADS ON ALL BOLTS	=	6415.8 POUNDS
THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS	=	-1415.8 POUNDS
DIFFERENCE PER BOLT	=	-707.9 POUNDS



HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	C037	-2.14	0.64	3124.5	-1.00
B	C034	-2.04	1.38	3299.8	3.98

TEST CASE 220
SPECIMEN 1D6

TOTAL SURVEY LOAD	=	3000.0 POUNDS
THE SUM OF THE AXIAL LOADS ON ALL BOLTS	=	-205.6 POUNDS
THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS	=	3205.6 POUNDS
DIFFERENCE PER BOLT	=	1602.8 POUNDS

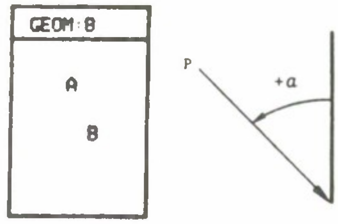


HOLE	BOLT ID	50 DEG. (VOLTS)	100 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	31	-2.32	0.50	-1139.4	-0.98
B	32	1.73	-0.90	937.3	5.10

Figure 3-29. Fastener Load Measurements Using Strain-Gaged Bolts for Test Cases 218 to 220.

TEST CASE 221
SPECIMEN 1D2

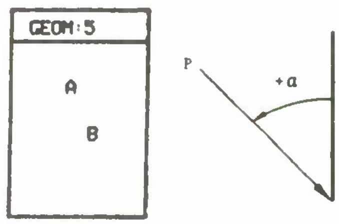
TOTAL SURVEY LOAD	=	3000.0	POUNDS
THE SUM OF THE AXIAL LOADS ON ALL BOLTS	=	2504.7	POUNDS
THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS	=	495.3	POUNDS
DIFFERENCE PER BOLT	=	247.6	POUNDS



HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	31	-2.76	0.90	1338.7	0.69
B	32	-2.32	0.97	1167.1	2.37

TEST CASE 222
SPECIMEN 1B34

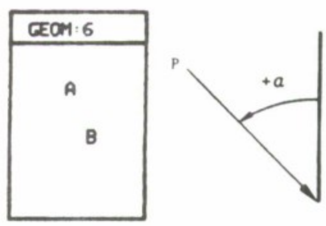
TOTAL SURVEY LOAD	=	3000.0	POUNDS
THE SUM OF THE AXIAL LOADS ON ALL BOLTS	=	3291.8	POUNDS
THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS	=	-291.8	POUNDS
DIFFERENCE PER BOLT	=	-145.9	POUNDS



HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	C11	-3.02	0.23	1787.9	-2.71
B	C33	1.24	3.03	1505.9	-0.35

TEST CASE 223
SPECIMEN 213

TOTAL SURVEY LOAD	=	5000.0	POUNDS
THE SUM OF THE AXIAL LOADS ON ALL BOLTS	=	4129.9	POUNDS
THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS	=	870.1	POUNDS
DIFFERENCE PER BOLT	=	435.1	POUNDS



HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	D34	2.01	-0.76	2121.5	-4.13
B	D37	1.46	-0.55	2024.0	5.72

Figure 3-30. Fastener Load Measurements Using Strain-Gaged Bolts for Test Cases 221 to 223.

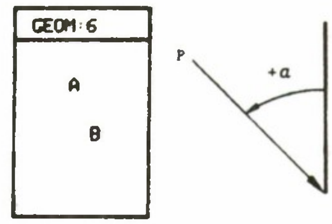
TEST CASE 224
SPECIMEN 313

TOTAL SURVEY LOAD = 5000.0 POUNDS

THE SUM OF THE AXIAL LOADS ON ALL BOLTS = 4918.6 POUNDS

THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS = 81.4 POUNDS

DIFFERENCE PER BOLT = 40.7 POUNDS



HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	D36	2.31	-0.34	2444.0	-3.66
B	D35	1.43	-1.69	2480.8	1.77

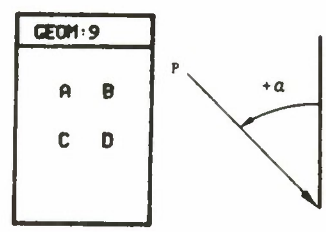
TEST CASE 225
SPECIMEN 183

TOTAL SURVEY LOAD = 6000.0 POUNDS

THE SUM OF THE AXIAL LOADS ON ALL BOLTS = 5665.6 POUNDS

THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS = 334.4 POUNDS

DIFFERENCE PER BOLT = 83.6 POUNDS



HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	11	-3.45	0.86	1647.2	3.18
B	12	-1.71	-3.58	1188.5	2.85
C	31	-2.89	0.92	1394.8	0.45
D	33	1.59	3.80	1439.7	-1.67

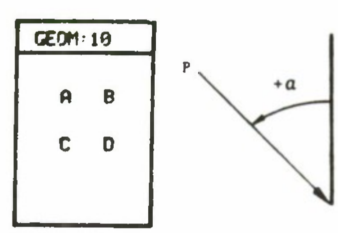
TEST CASE 226
SPECIMEN 184

TOTAL SURVEY LOAD = 10000.0 POUNDS

THE SUM OF THE AXIAL LOADS ON ALL BOLTS = 10204.3 POUNDS

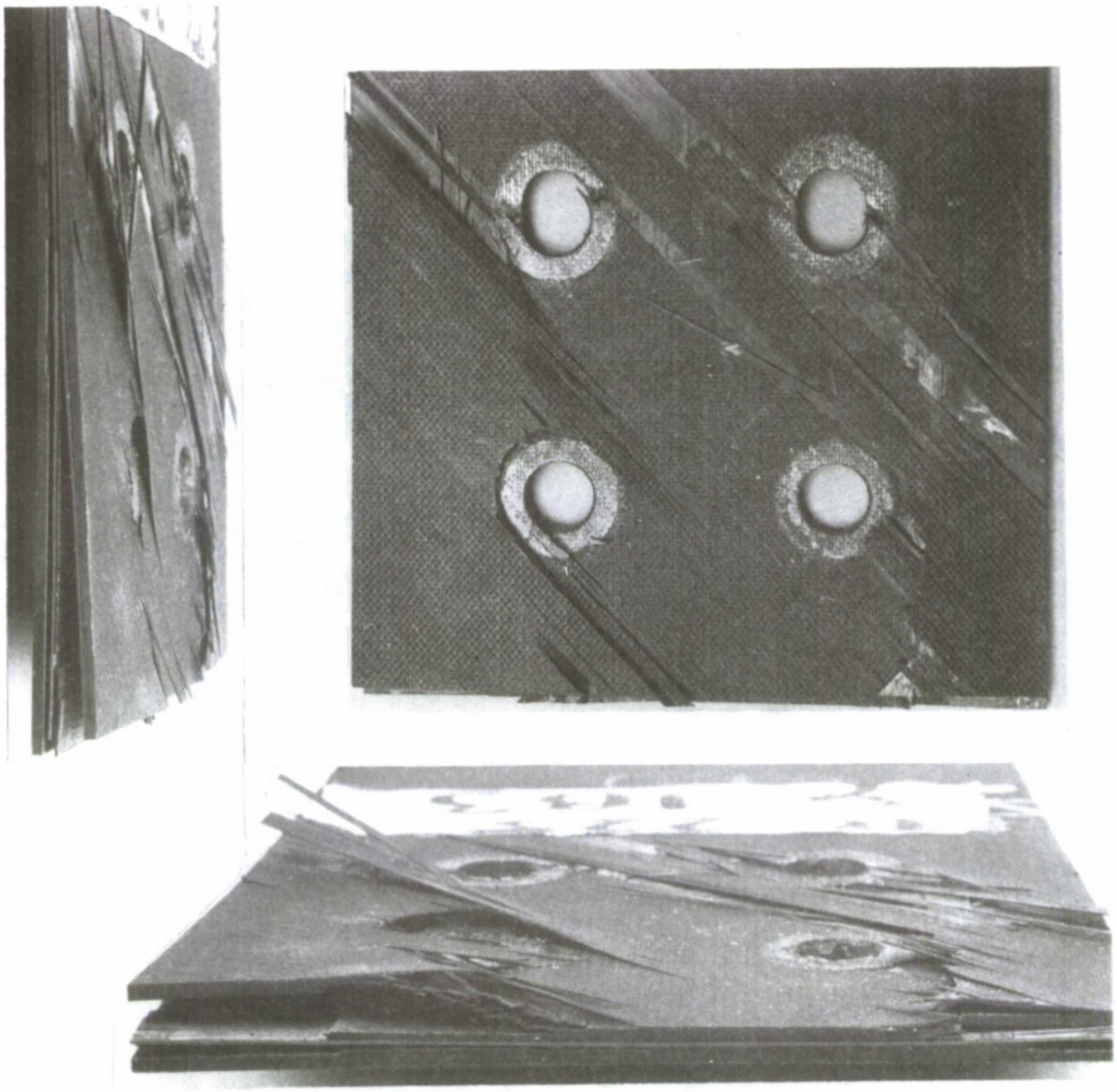
THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS = -204.3 POUNDS

DIFFERENCE PER BOLT = -51.1 POUNDS



HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	D34	2.41	-0.82	2507.1	-5.14
B	D35	1.58	-1.87	2743.0	1.79
C	D36	2.20	-0.42	2375.1	-2.29
D	D37	1.80	-0.97	2623.1	8.78

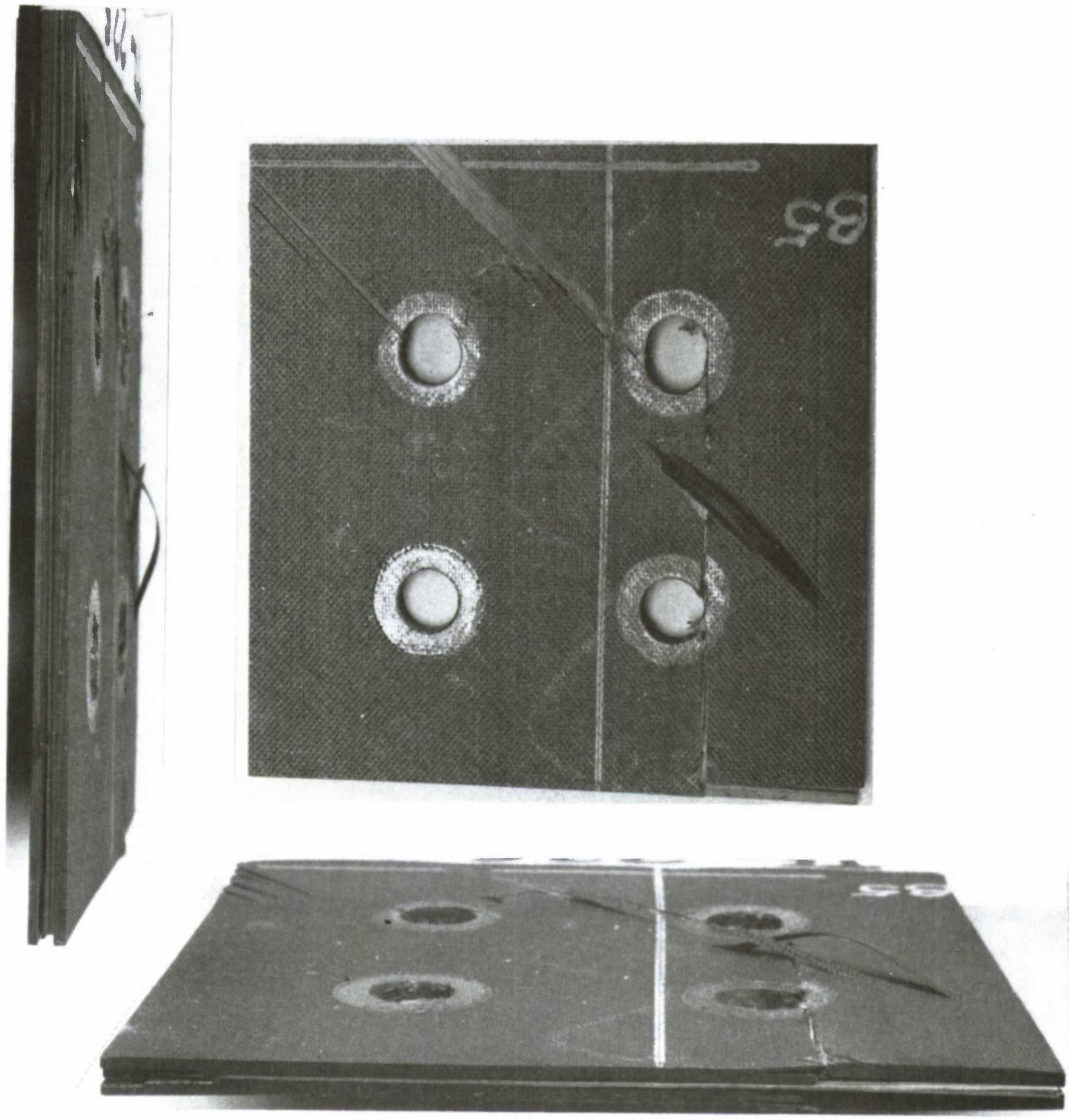
Figure 3-31. Fastener Load Measurements Using Strain-Gaged Bolts for Test Cases 224 to 226.



TC 225

SPEC 1B3

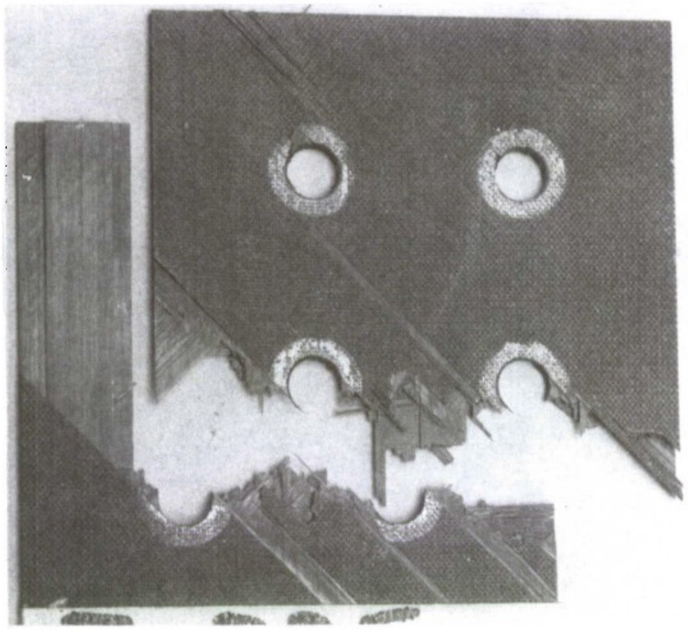
Figure 3-32. Failure Specimen from Test Case 225.



TC 225

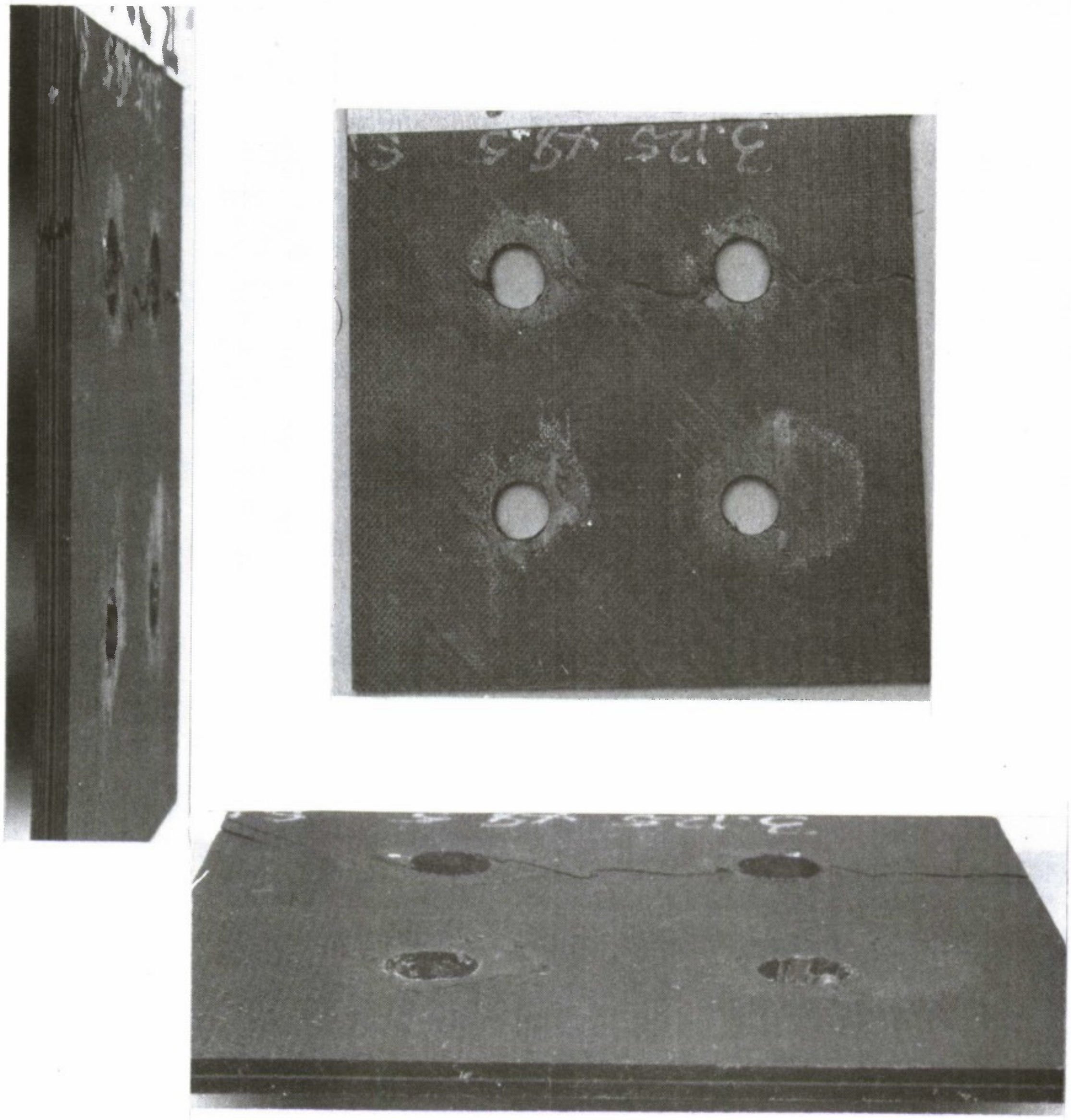
SPEC 1B5

Figure 3-32. A Different Failure Mode Observed in Test Case 225. (Continued).



TC 225
SPEC 1B1

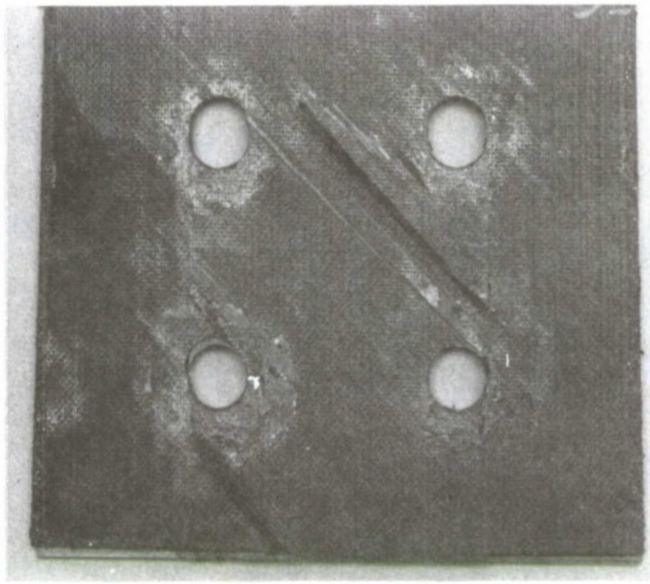
Figure 3-32. A Different Failure Mode Observed in Test Case 225. (Concluded).



TC 226

SPEC 1B6

Figure 3-33. Failed Specimen from Test Case 226.



TC 227
SPEC 1B7

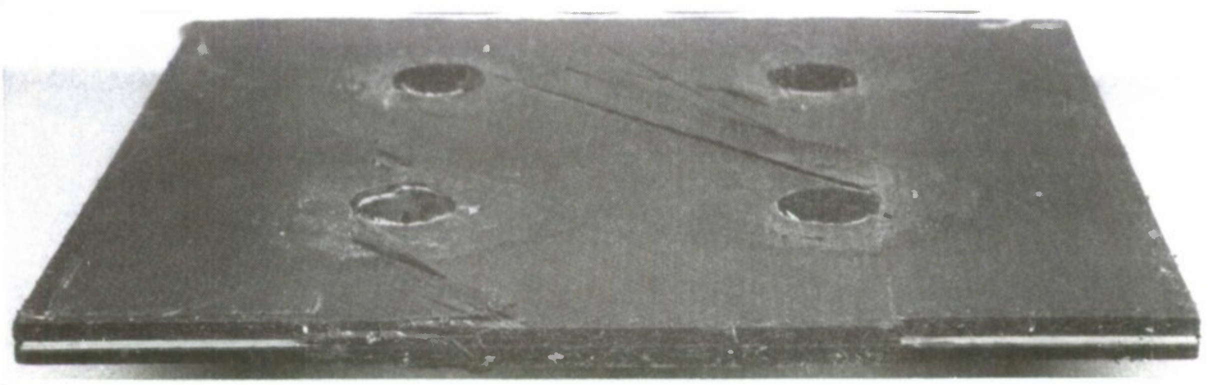
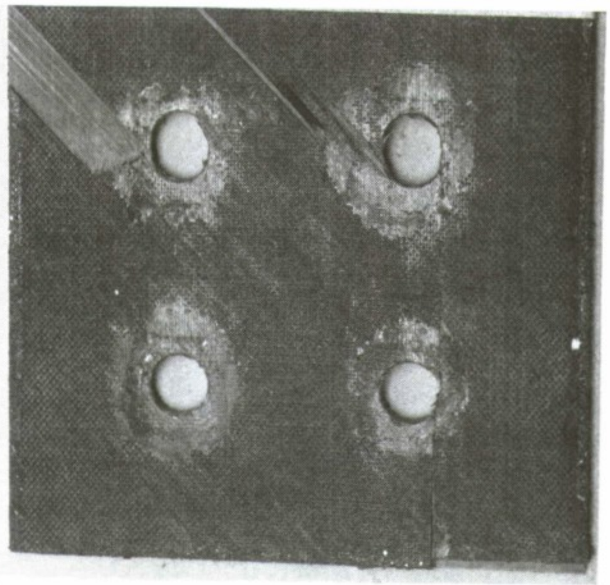


Figure 3-34. Failed Specimen from Test Case 227.



TC 227
SPEC 1B9

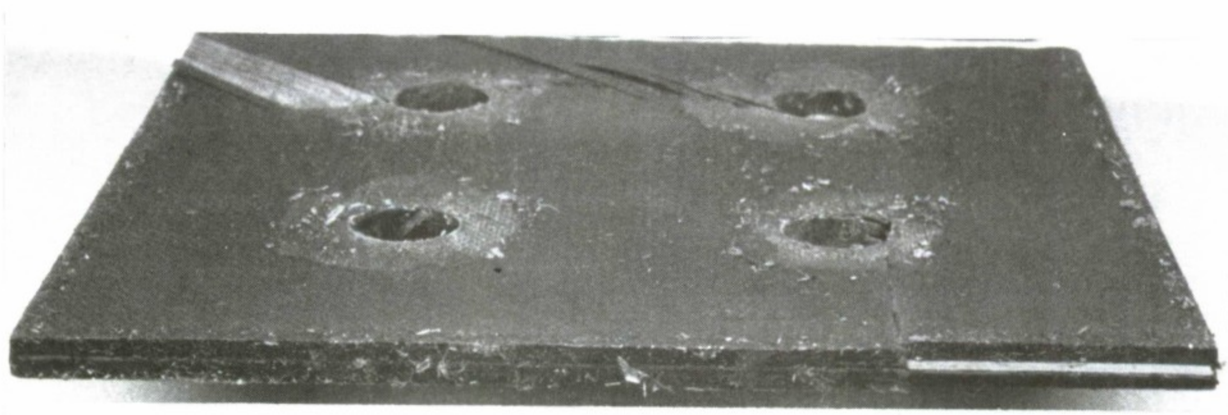
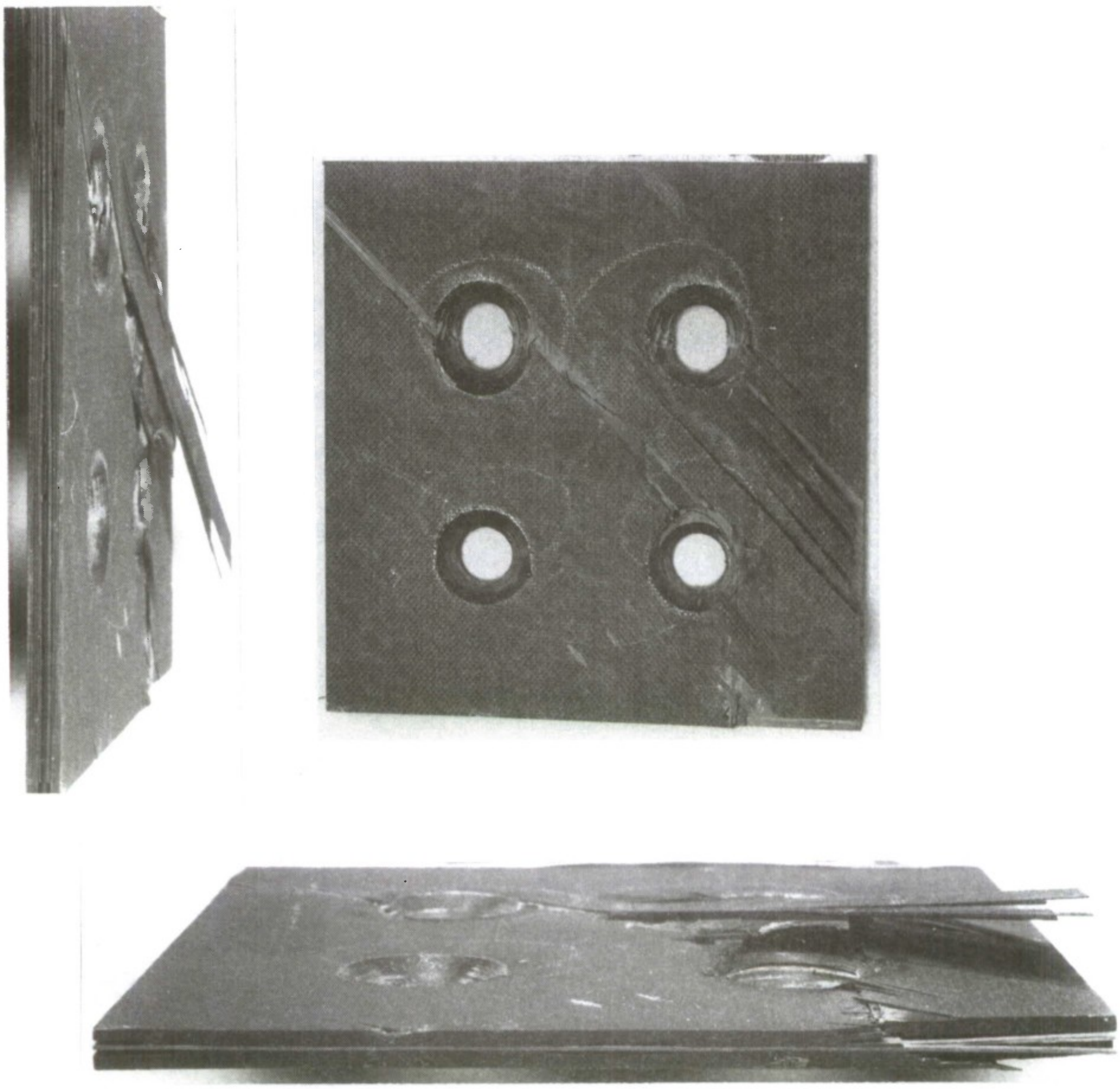


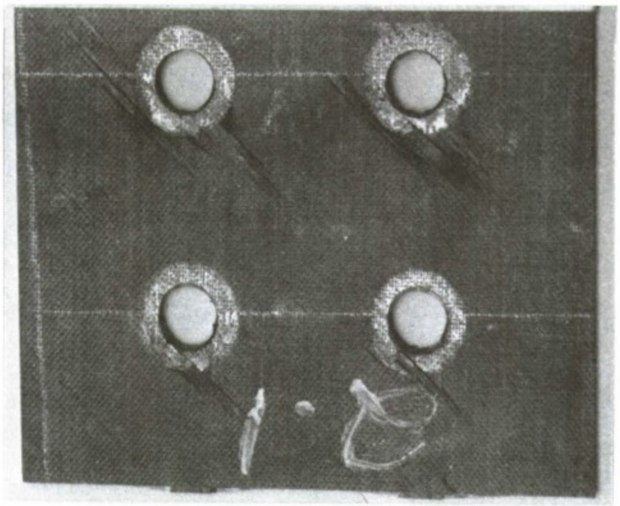
Figure 3-34. A Different Failure Mode Observed in Test Case 227. (Concluded).



TC 228

SPEC 1B12

Figure 3-35. Failed Specimen from Test Case 228.



TC 229
SPEC 2.1

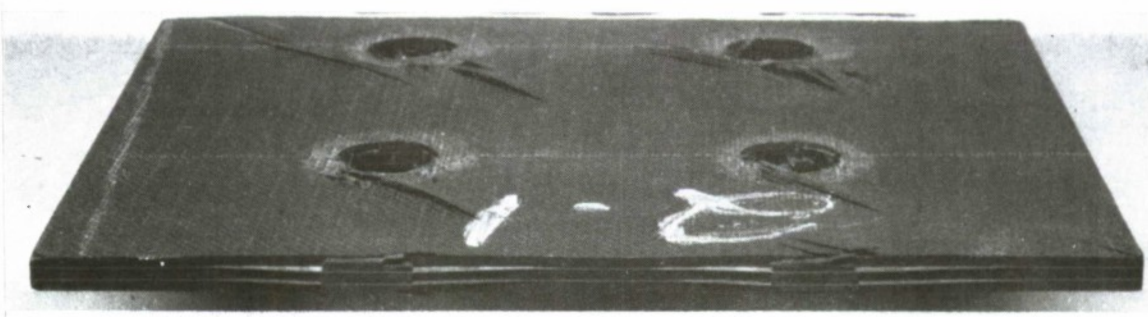
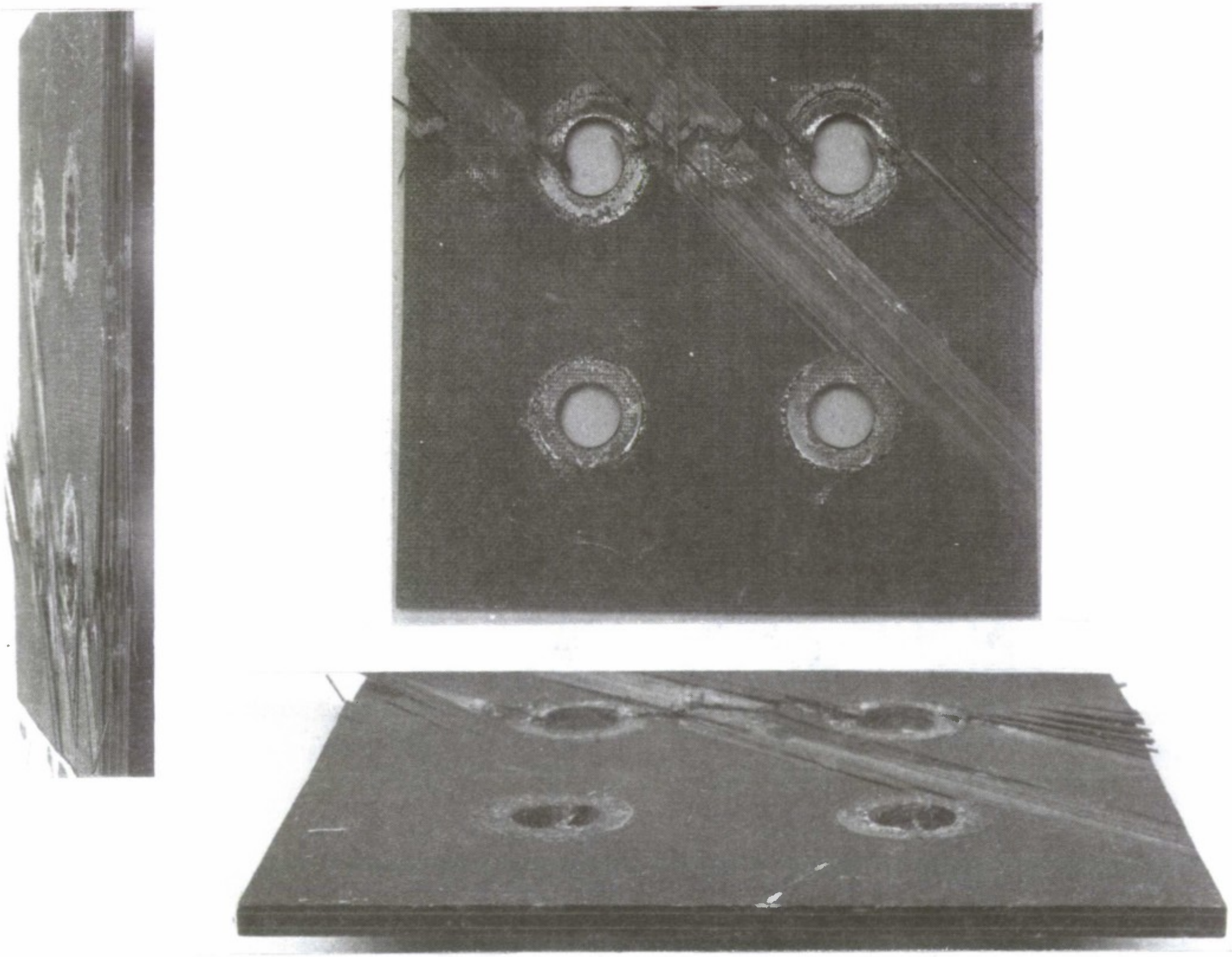
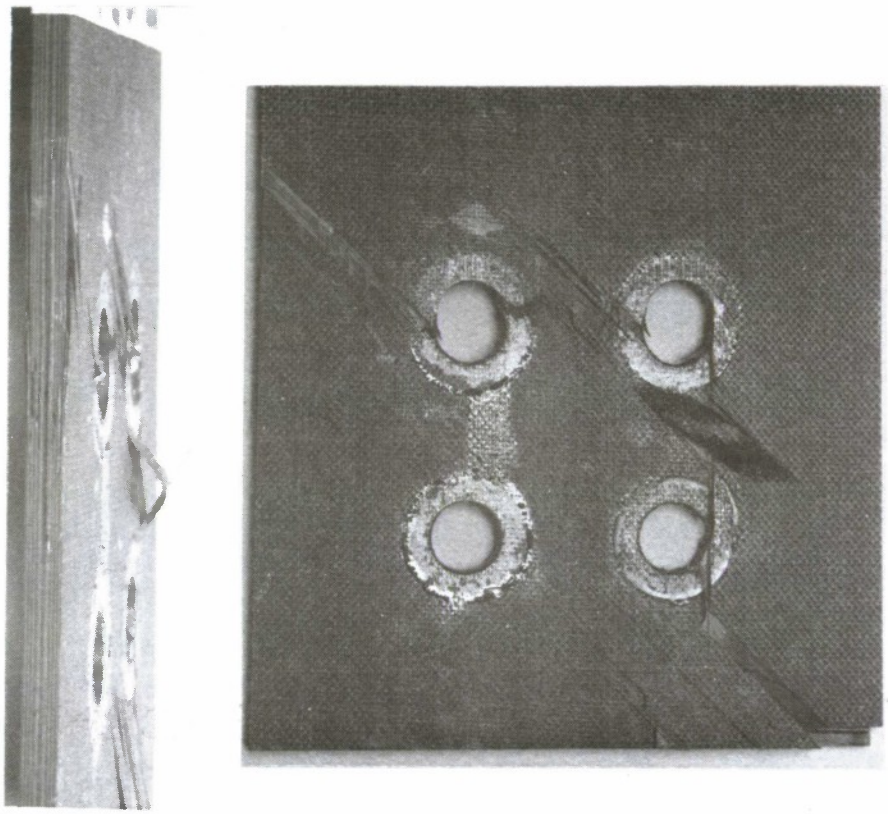


Figure 3-36. Failed Specimen from Test Case 229.

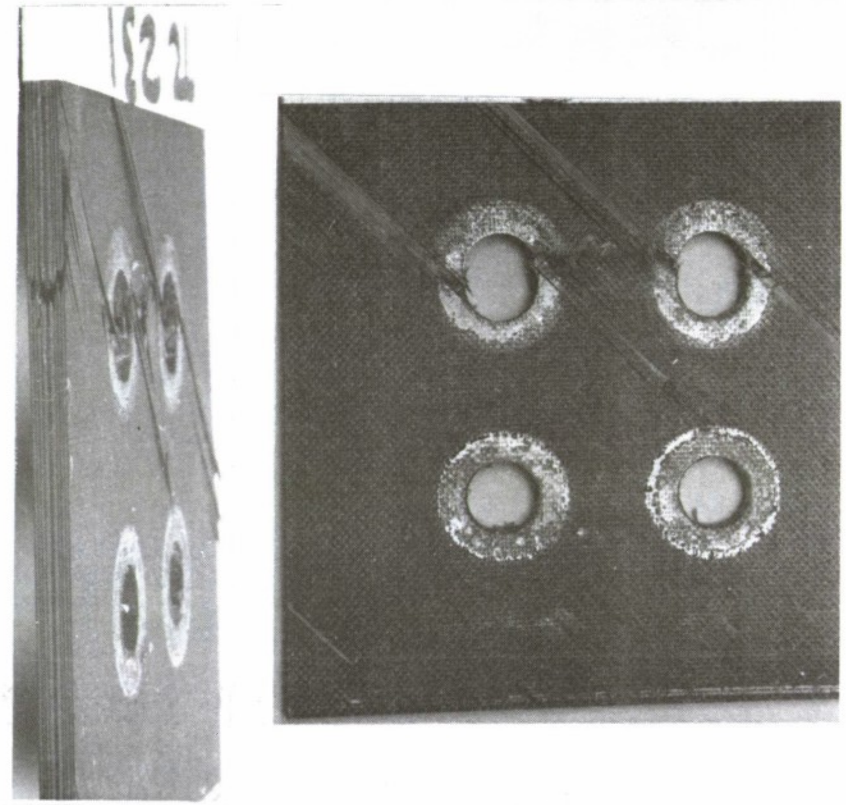


TC 230
SPEC 3.1

Figure 3-37. Failed Specimen from Test Case 230.

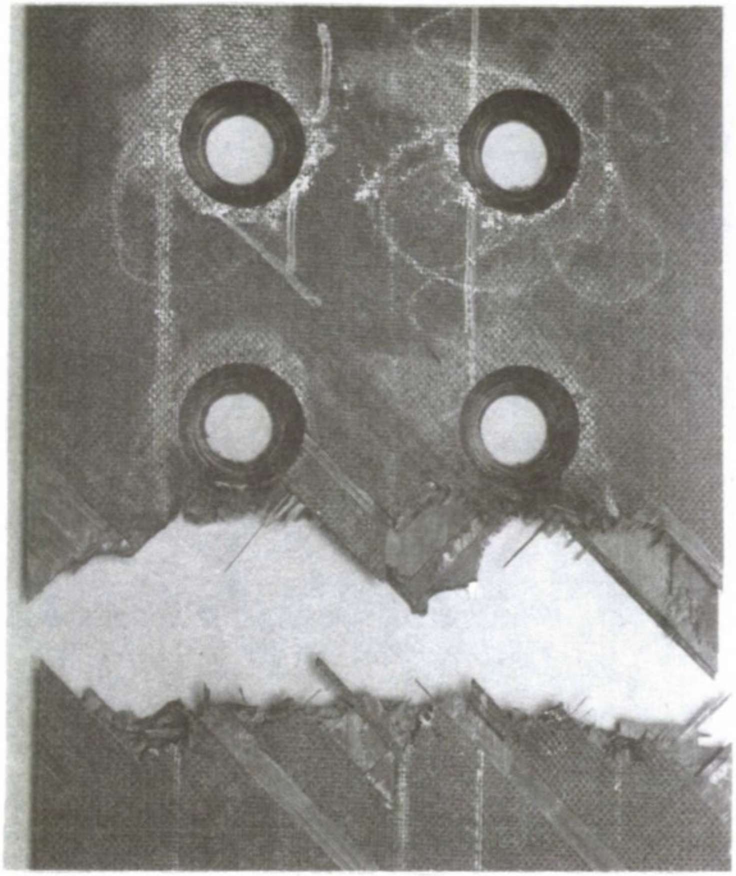


TC 231
SPEC 1C4

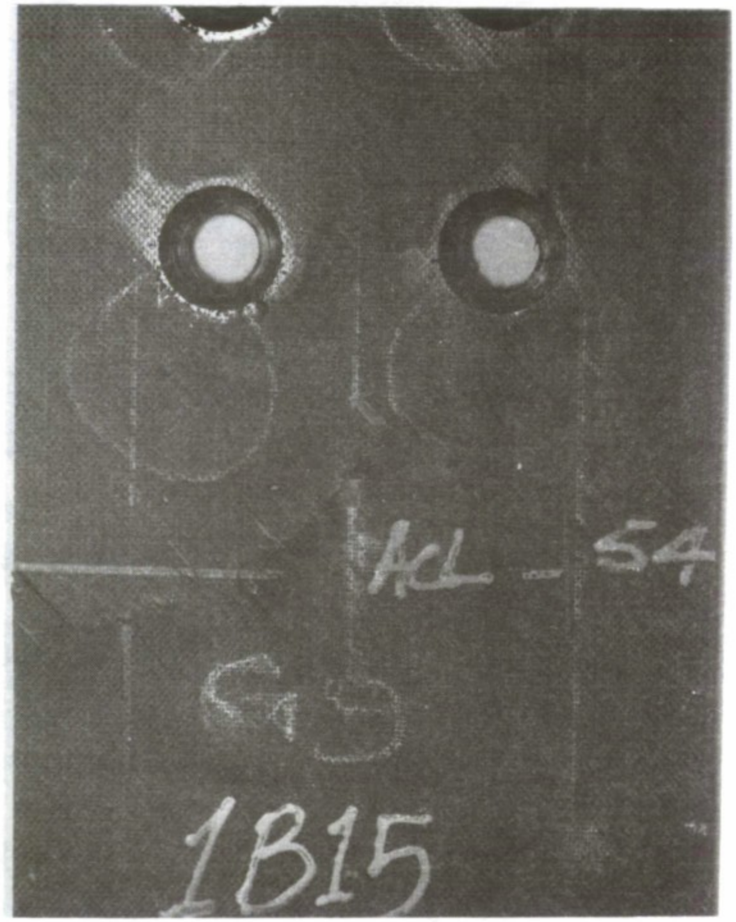


TC 231
SPEC 1C6

Figure 3-38. Failed Specimens from Test Case 231.



TC 232
SPEC 1B13

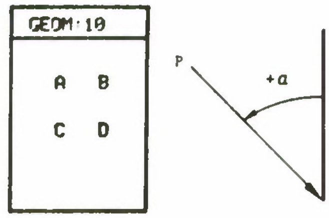


TC 232
SPEC 1B15

Figure 3-39. Failed Specimens from Test Case 232.

TEST CASE 227
SPECIMEN 1B9

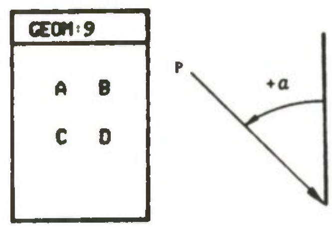
TOTAL SURVEY LOAD	= 10000.0	POUNDS
THE SUM OF THE AXIAL LOADS ON ALL BOLTS	= 9294.9	POUNDS
THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS	= 705.1	POUNDS
DIFFERENCE PER BOLT	= 176.3	POUNDS



HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	D34	2.17	-0.78	2274.0	-4.62
B	D35	1.57	-1.60	2545.0	-0.26
C	D36	1.89	-0.40	2060.2	-1.66
D	D37	1.73	-0.75	2441.3	6.84

TEST CASE 228
SPECIMEN 1B10

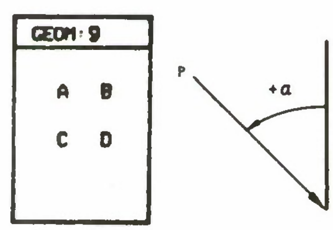
TOTAL SURVEY LOAD	= 6000.0	POUNDS
THE SUM OF THE AXIAL LOADS ON ALL BOLTS	= 7175.9	POUNDS
THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS	= -1175.9	POUNDS
DIFFERENCE PER BOLT	= -294.0	POUNDS



HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	C31	-2.79	0.45	1751.4	-1.36
B	C33	1.31	2.80	1363.1	3.34
C	C11	-3.35	0.45	2073.3	-0.11
D	C12	-1.49	-3.29	2010.8	-8.05

TEST CASE 229
SPECIMEN 2.2

TOTAL SURVEY LOAD	= 6000.0	POUNDS
THE SUM OF THE AXIAL LOADS ON ALL BOLTS	= 5982.9	POUNDS
THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS	= 17.1	POUNDS
DIFFERENCE PER BOLT	= 4.3	POUNDS

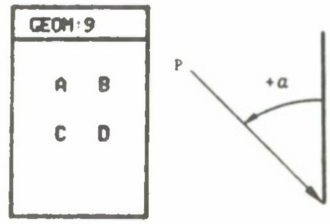


HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	11	-3.86	0.48	1712.1	-1.37
B	12	-1.78	-4.01	1344.0	0.75
C	31	-2.98	1.19	1515.7	2.86
D	33	1.70	3.77	1413.5	0.45

Figure 3-40. Fastener Load Measurements Using Strain-Gaged Bolts for Test Cases 227 to 229.

TEST CASE 230
SPECIMEN 32

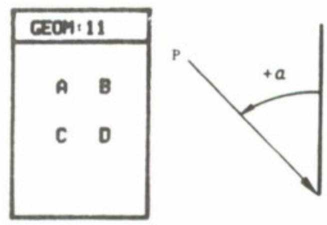
TOTAL SURVEY LOAD	=	6000.0	POUNDS
THE SUM OF THE AXIAL LOADS ON ALL BOLTS	=	5354.1	POUNDS
THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS	=	645.9	POUNDS
DIFFERENCE PER BOLT	=	161.5	POUNDS



HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	31	-2.87	1.02	1418.7	1.58
B	32	-2.44	1.22	1286.9	4.53
C	33	1.61	3.40	1266.2	1.96
D	12	-1.91	-4.16	1388.2	1.69

TEST CASE 231
SPECIMEN 1C4

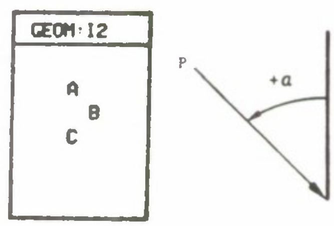
TOTAL SURVEY LOAD	=	6000.0	POUNDS
THE SUM OF THE AXIAL LOADS ON ALL BOLTS	=	5512.6	POUNDS
THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS	=	487.4	POUNDS
DIFFERENCE PER BOLT	=	121.8	POUNDS



HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	31	-2.74	1.06	1382.4	2.50
B	32	-2.08	1.50	1247.2	9.46
C	33	1.58	3.67	1384.9	-0.89
D	12	-2.10	-4.55	1517.4	1.84

TEST CASE 233
SPECIMEN 1C10

TOTAL SURVEY LOAD	=	4500.0	POUNDS
THE SUM OF THE AXIAL LOADS ON ALL BOLTS	=	3668.1	POUNDS
THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS	=	831.9	POUNDS
DIFFERENCE PER BOLT	=	277.3	POUNDS



HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	31	-2.35	1.06	1236.2	4.28
B	32	-2.44	1.21	1283.8	4.42
C	33	1.42	3.09	1155.5	1.02

Figure 3-41. Fastener Load Measurements Using Strain-Gaged Bolts for Test Cases 230, 231 and 233.

The strain-gaged bolts were used only to obtain the fractional load carried by each fastener, and were subsequently replaced by regular fasteners. The differences between the two situations will affect the actual fastener load fraction corresponding to specimen failure.

3.4 Results from Tests on Joints with Three Fasteners in Staggered Patterns

Test cases 233 to 241 in Table 2-1 address tests on joints with three fasteners in two staggered patterns. Failed specimens from these tests are presented in Figures 3-42 to 3-50, illustrating the various failure modes listed in Table 3-1. The joint failure loads and the observed failure modes are affected by fastener spacing (S_L and S_T), load eccentricity, fastener head geometry, test environment, and laminate layup.

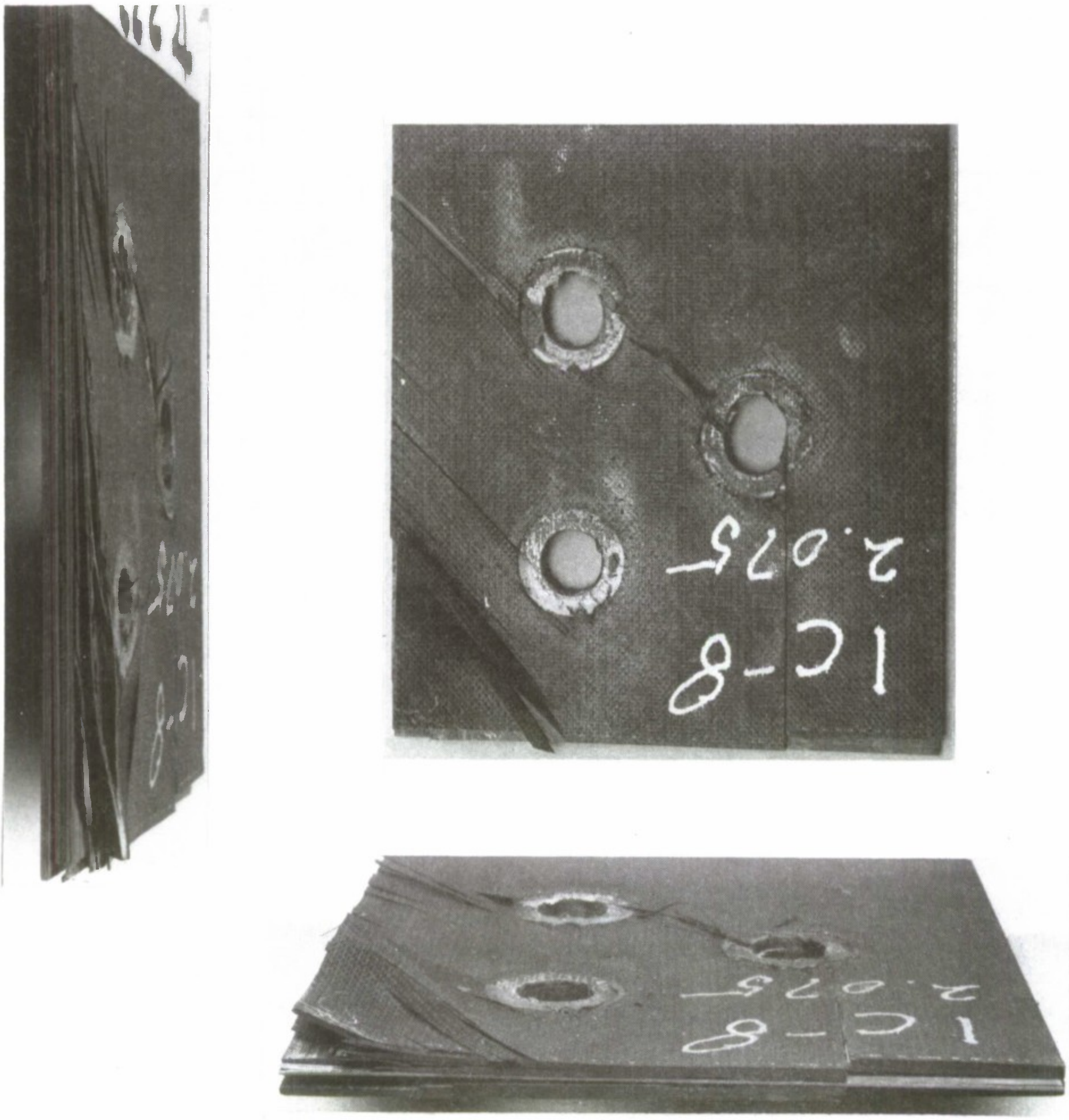
In most of the test cases, the stress concentration regions at the three fastener locations interacted among themselves to affect the failure load value and the load distribution among the fasteners. Figures 3-41, 3-51, 3-52 and 3-53 present the fractional fastener loads, corresponding to the survey load level, based on strain-gaged bolt measurements.

For $S_L/D = 4$ and $S_T/D = 3$, the 50/40/10 laminates exhibited a cleavage/ net section mode of failure under tension. Local bearing, accompanied by a net section compressive failure, was observed under compression. The 70/20/10 laminates failed in a partial shear-out mode, and the 30/60/10 laminates failed via local bearing, under tensile loading. When S_L/D was reduced to 2 from 4, the failure mode in 50/40/10 laminates under tension switched from cleavage/ net section to partial shear-out.

3.5 Results from Tests on Joints with Six or Eight Fasteners and a Neighboring Cut-out

Test cases 242 to 247 in Table 2-1 address tests on joints with six fasteners and a one inch diameter neighboring cut-out. The size and location of the circular cut-out were selected to make the fastener and cut-out locations equally critical. All the test laminates were 40-ply layups (see Table 2-1).

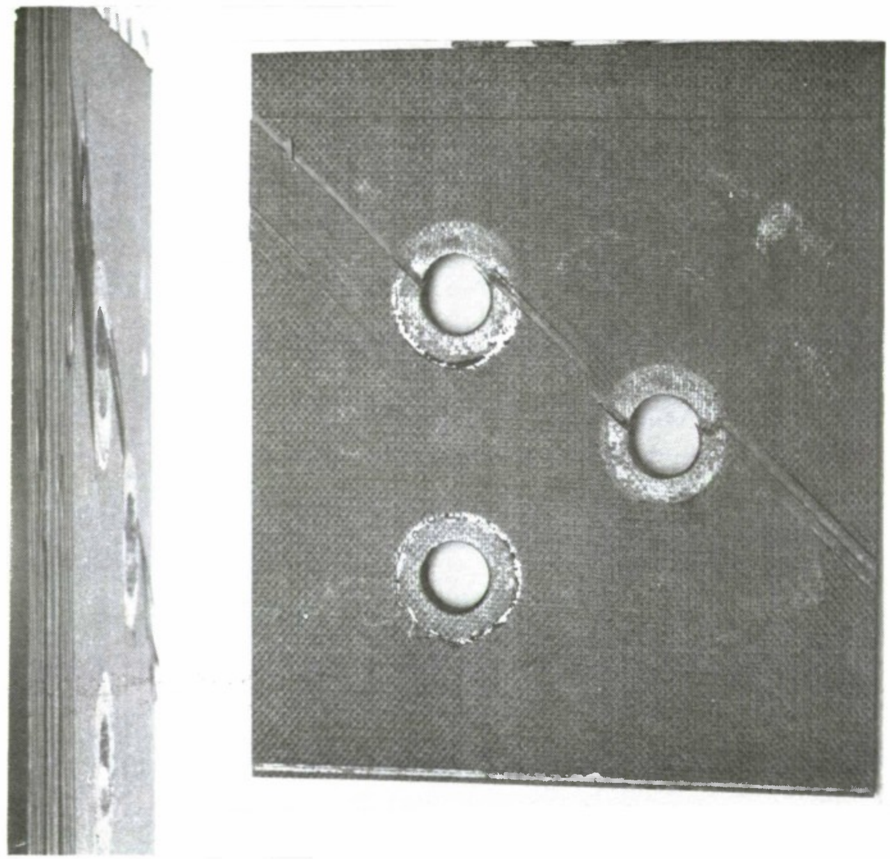
In a double shear configuration, under tensile loading, 50/40/10 laminates failed in a net section mode, along the fastener row near the circular cut (see Figure 3-54). In a single shear configuration, the same laminates exhibited net section failures that are either across the circular



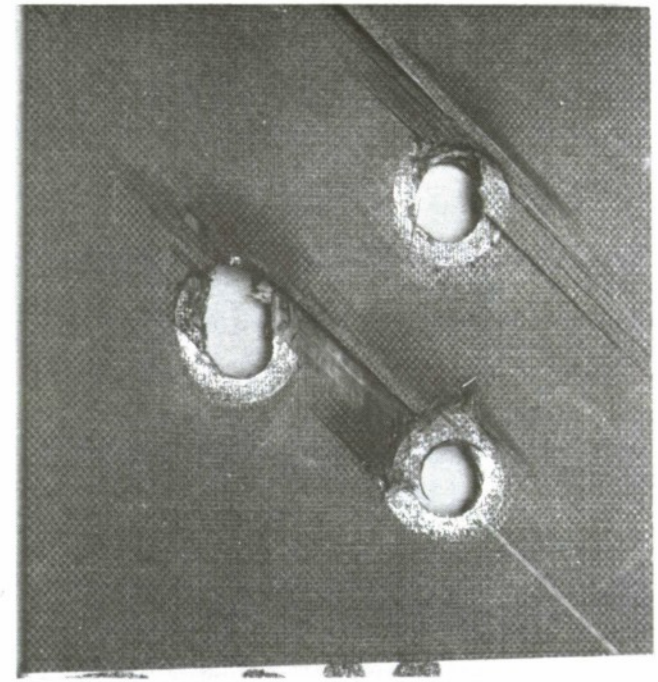
TC 233

SPEC 1C8

Figure 3-42. Failed Specimen from Test Case 233.

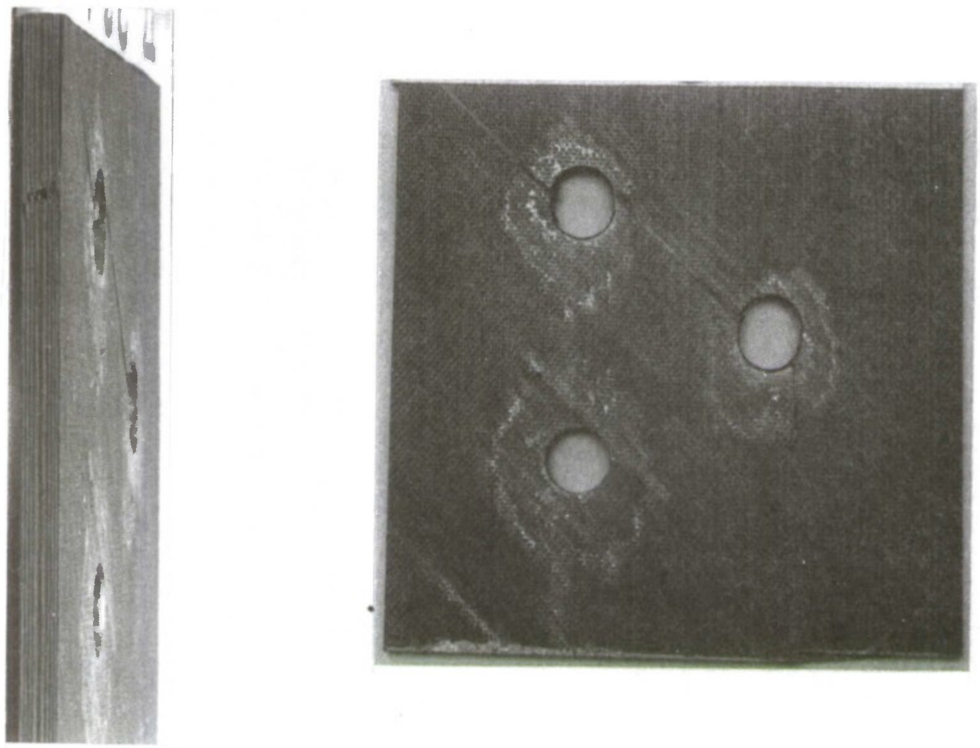


TC 233
SPEC 1C10



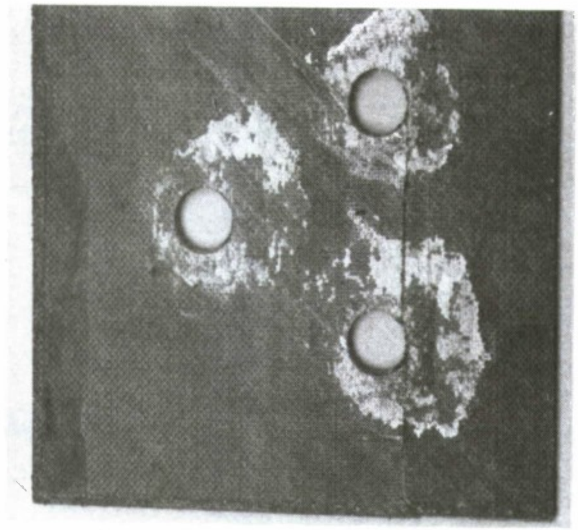
TC 233
SPEC 1C11

Figure 3-42. Different Failure Modes Observed in Test Case 233, (Concluded).



TC 234
SPEC 1C15

Figure 3-43. Failed Specimen from Test Case 234.



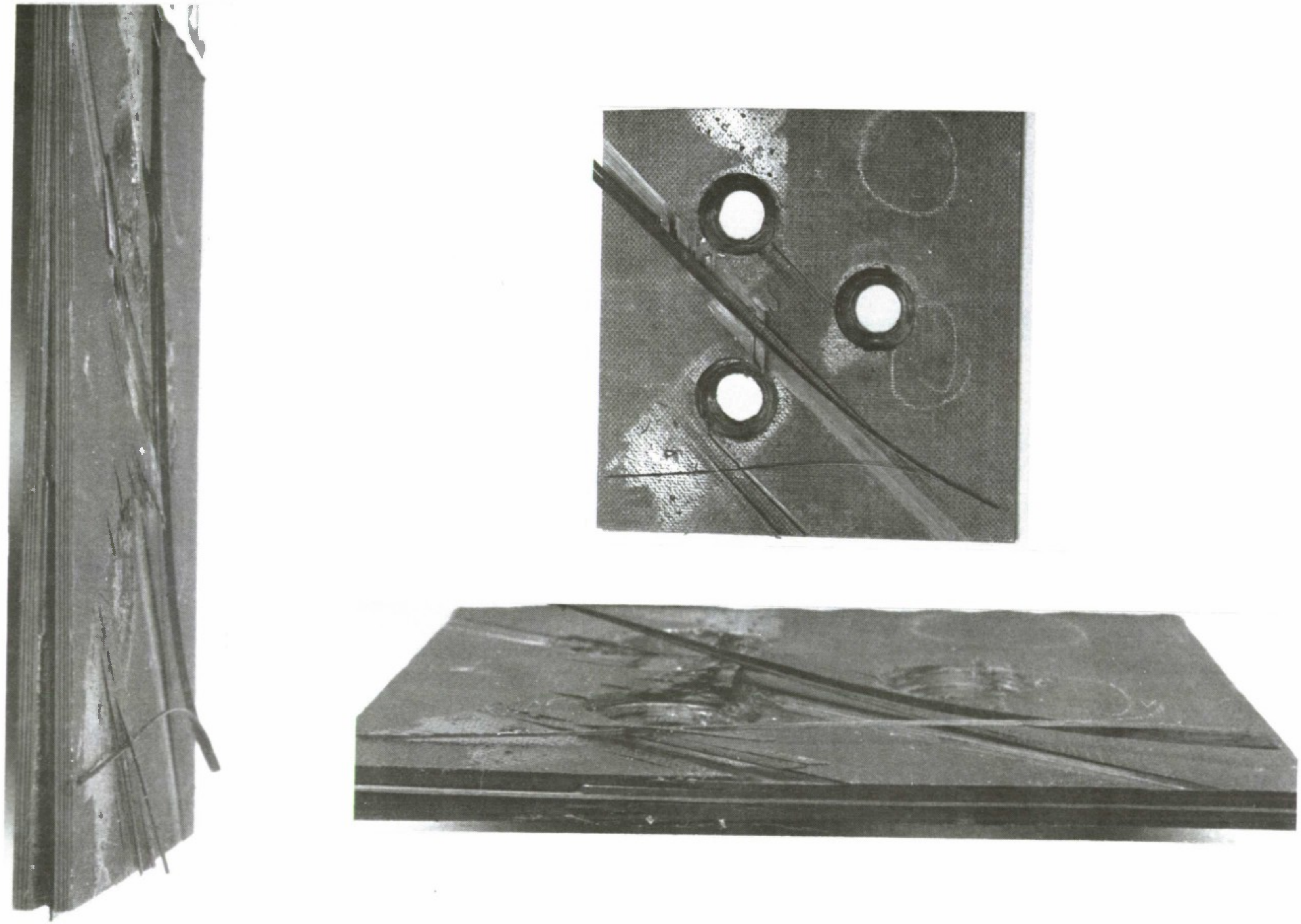
TC 235
SPEC 1C21

Figure 3-44. Failed Specimen from Test Case 235.

TC 236

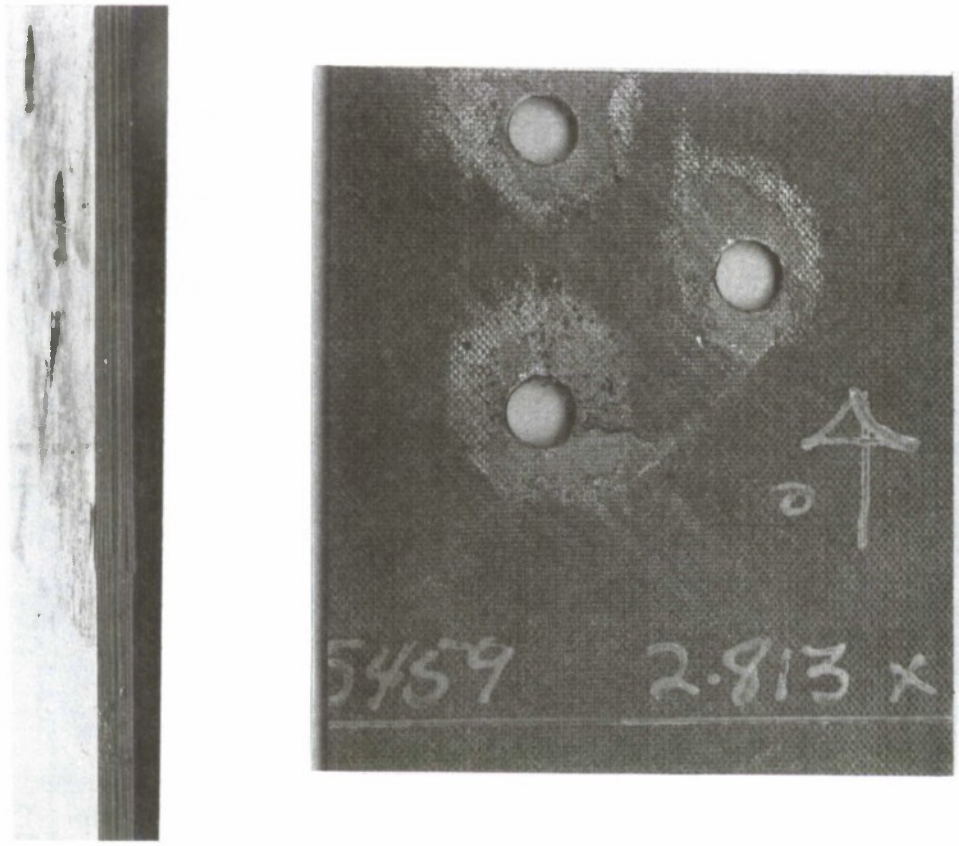
SPEC 1C20

Figure 3-45. Failed Specimens from Test Case 236.



TC 236
SPEC 1C22

Figure 3-45. A Different Failure Mode Observed in Test Case 236. (Concluded).



TC 237
SPEC 1C27

Figure 3-46. Failed Specimen from Test Case 237.

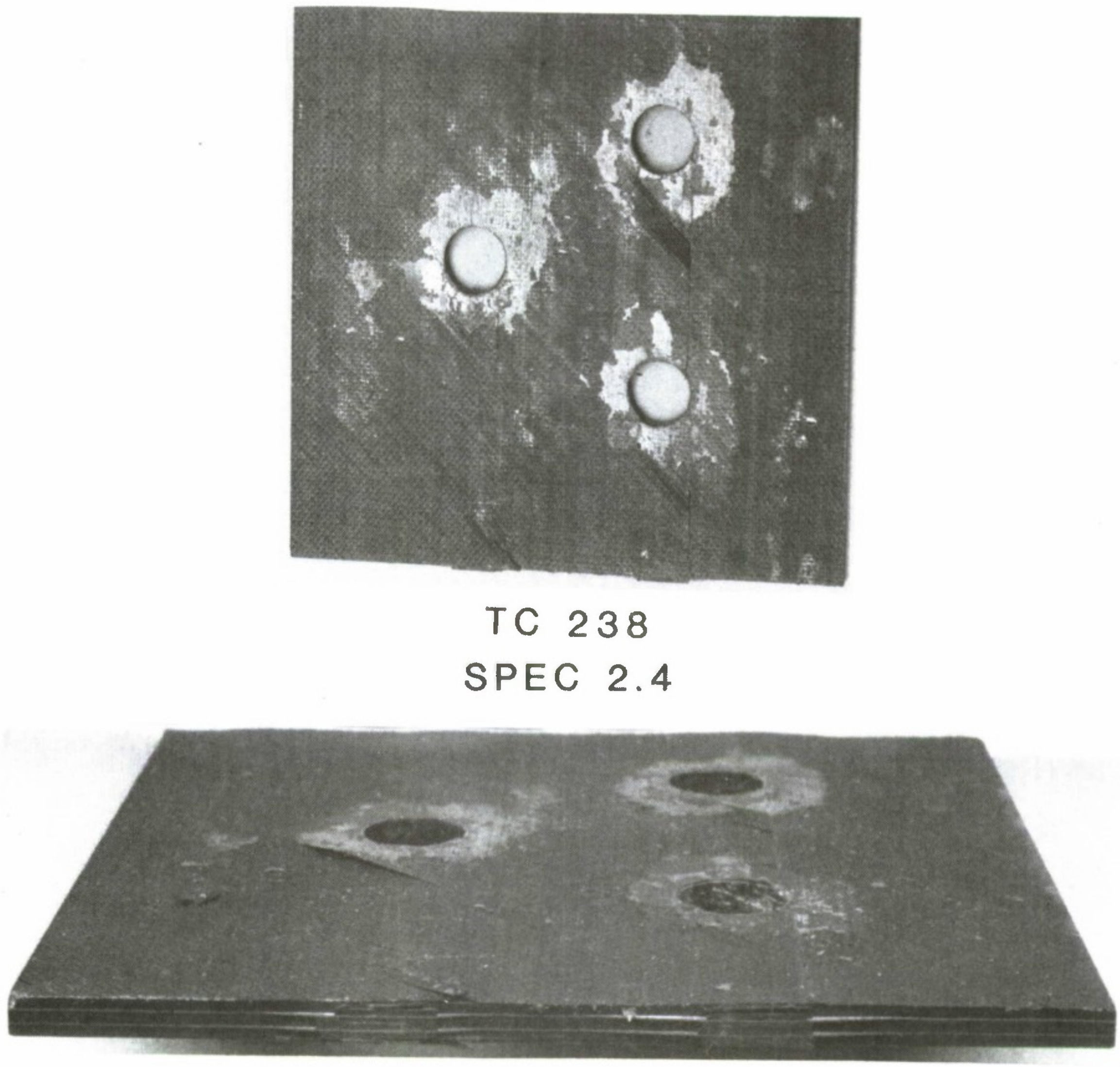
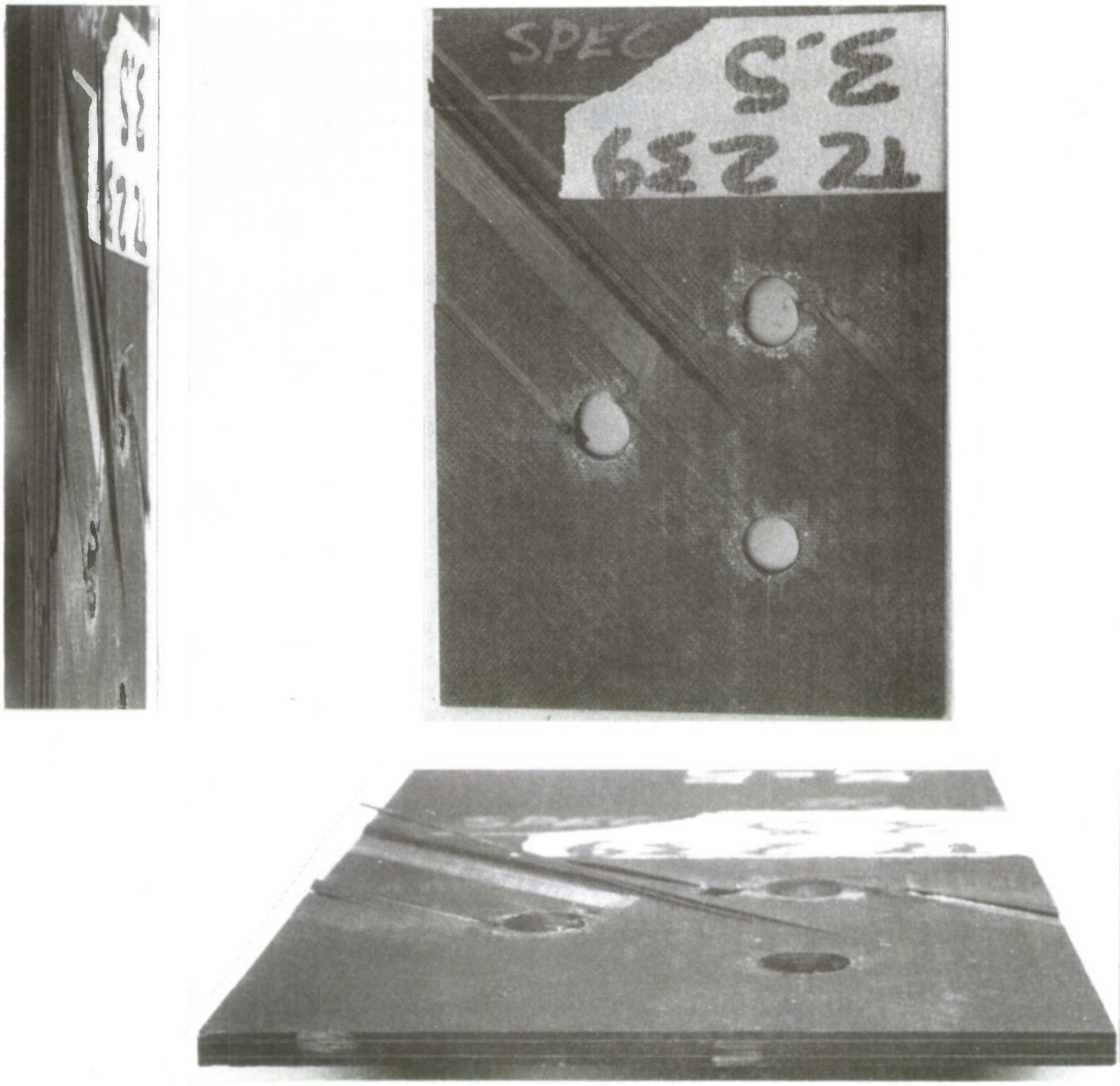


Figure 3-47. Failed Specimen from Test Case 238.



TC 239

SPEC 3.5

Figure 3-48. Failed Specimen from Test Case 239.

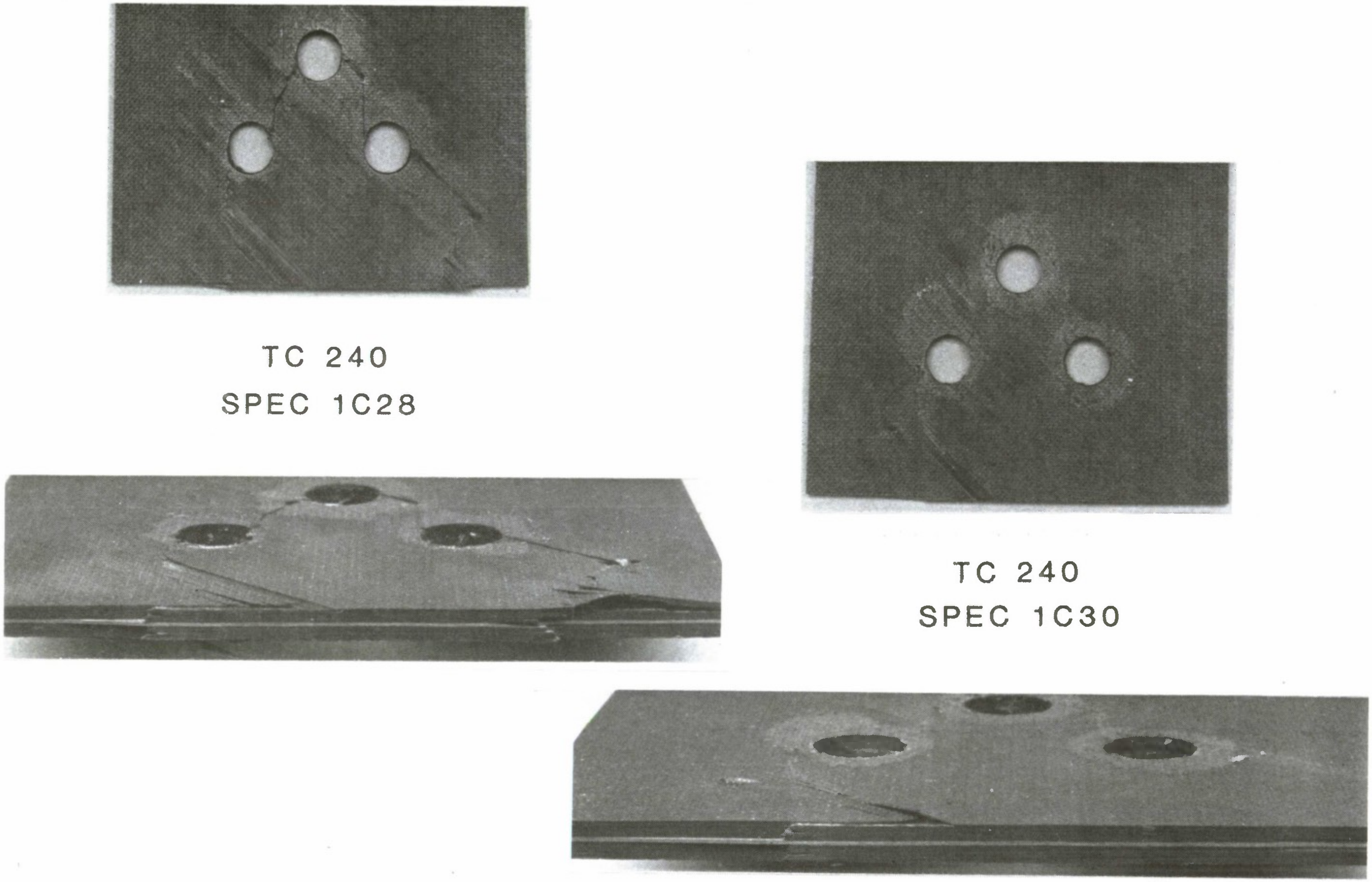
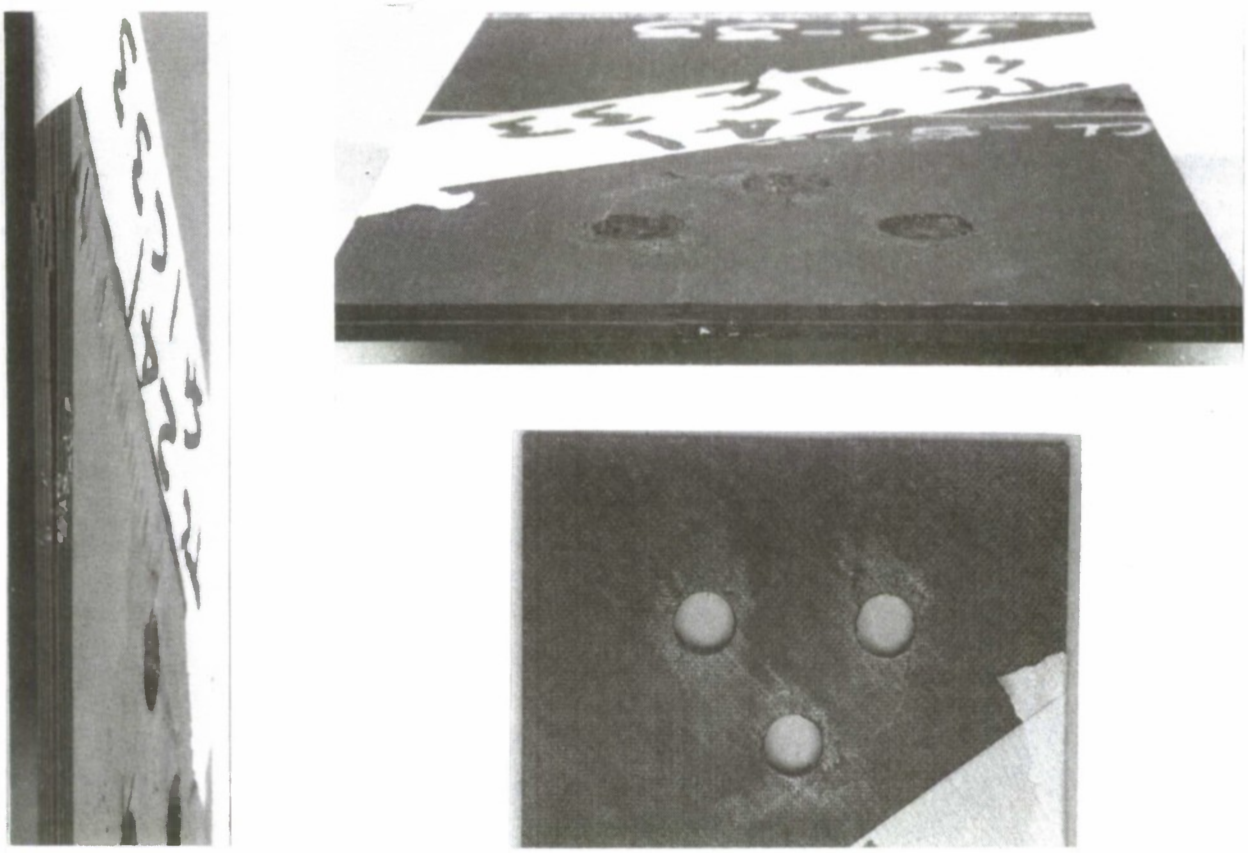


Figure 3-49. Failed Specimens from Test Case 240.



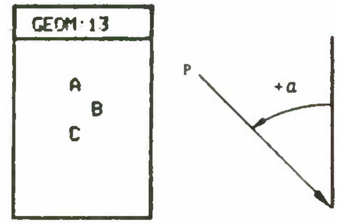
TC 241

SPEC 1C33

Figure 3-50. Failed Specimen from Test Case 241.

TEST CASE 234
SPECIMEN 1C1S

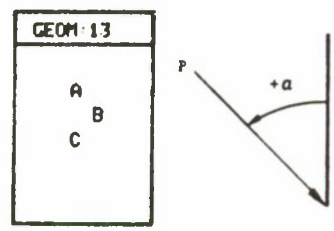
TOTAL SURVEY LOAD	= 7500.0	POUNDS
THE SUM OF THE AXIAL LOADS ON ALL BOLTS	= 6719.8	POUNDS
THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS	= 780.2	POUNDS
DIFFERENCE PER BOLT	= 260.1	POUNDS



HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	D35	0.84	-1.78	2044.3	9.53
B	D37	2.27	-0.74	3096.1	4.69
C	D34	1.84	0.07	1689.5	-16.72

TEST CASE 235
SPECIMEN 1C21

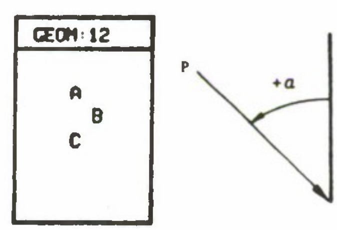
TOTAL SURVEY LOAD	= 7500.0	POUNDS
THE SUM OF THE AXIAL LOADS ON ALL BOLTS	= 6455.9	POUNDS
THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS	= 1044.1	POUNDS
DIFFERENCE PER BOLT	= 348.0	POUNDS



HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	D34	1.85	-1.16	2163.8	1.77
B	D35	1.36	-1.18	2064.4	-2.44
C	D37	1.62	-0.60	2241.2	5.60

TEST CASE 236
SPECIMEN 1C22

TOTAL SURVEY LOAD	= 4500.0	POUNDS
THE SUM OF THE AXIAL LOADS ON ALL BOLTS	= 4592.6	POUNDS
THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS	= -92.6	POUNDS
DIFFERENCE PER BOLT	= -30.9	POUNDS



HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	C31	-2.67	0.50	1704.5	-0.38
B	C11	-2.66	0.48	1707.2	1.82
C	C33	0.98	2.38	1181.8	-0.20

Figure 3-51. Fastener Load Measurements Using Strain-Gaged Bolts for Test Cases 234 to 236.

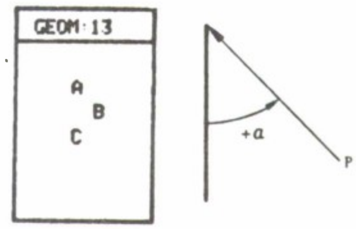
TEST CASE 237
SPECIMEN 1C27

TOTAL SURVEY LOAD = 7500.0 POUNDS

THE SUM OF THE AXIAL LOADS ON ALL BOLTS = 8288.2 POUNDS

THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS = -788.2 POUNDS

DIFFERENCE PER BOLT = -262.7 POUNDS



HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	C036	-2.15	0.72	2842.4	0.88
B	C037	-1.92	0.94	3077.4	3.75
C	C034	-1.46	0.68	2375.2	-0.41

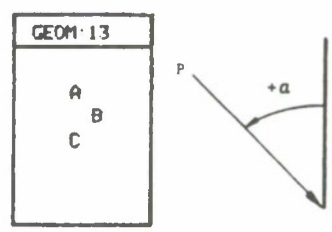
TEST CASE 238
SPECIMEN 2S

TOTAL SURVEY LOAD = 7500.0 POUNDS

THE SUM OF THE AXIAL LOADS ON ALL BOLTS = 5769.5 POUNDS

THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS = 1730.5 POUNDS

DIFFERENCE PER BOLT = 576.8 POUNDS



HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	D34	1.65	-0.95	1887.8	0.65
B	D35	1.30	-1.51	2236.7	1.53
C	D36	1.58	-0.19	1651.1	-4.54

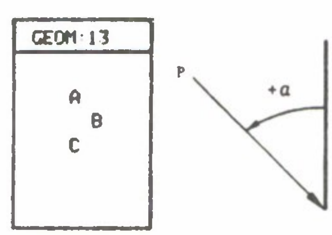
TEST CASE 239
SPECIMEN 3S

TOTAL SURVEY LOAD = 7500.0 POUNDS

THE SUM OF THE AXIAL LOADS ON ALL BOLTS = 6172.0 POUNDS

THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS = 1328.0 POUNDS

DIFFERENCE PER BOLT = 442.7 POUNDS

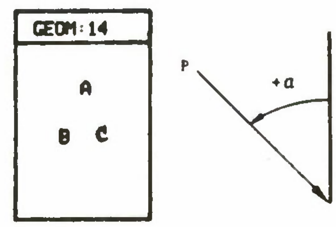


HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	D34	1.95	-0.87	2114.3	-2.40
B	D35	1.31	-1.77	2431.7	3.61
C	D36	1.68	0.02	1654.2	-9.22

Figure 3-52. Fastener Load Measurements Using Strain-Gaged Bolts for Test Cases 237 to 239.

TEST CASE 240
SPECIMEN 1C28

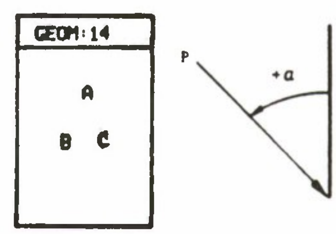
TOTAL SURVEY LOAD	= 7500.0	POUNDS
THE SUM OF THE AXIAL LOADS ON ALL BOLTS	= 6528.3	POUNDS
THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS	= 971.7	POUNDS
DIFFERENCE PER BOLT	= 323.9	POUNDS



HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	D34	1.70	-1.25	2085.2	3.97
B	D35	1.72	-1.26	2457.2	-4.64
C	D36	1.78	-0.49	1999.0	0.20

TEST CASE 241
SPECIMEN 1C33

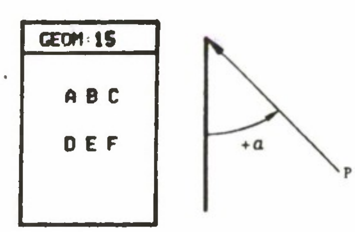
TOTAL SURVEY LOAD	= 7500.0	POUNDS
THE SUM OF THE AXIAL LOADS ON ALL BOLTS	= 9314.8	POUNDS
THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS	= -1814.8	POUNDS
DIFFERENCE PER BOLT	= -604.9	POUNDS



HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	C036	-2.21	1.07	3078.1	4.60
B	C037	-1.90	0.25	2683.3	-6.00
C	C034	-2.59	0.96	3581.9	-2.69

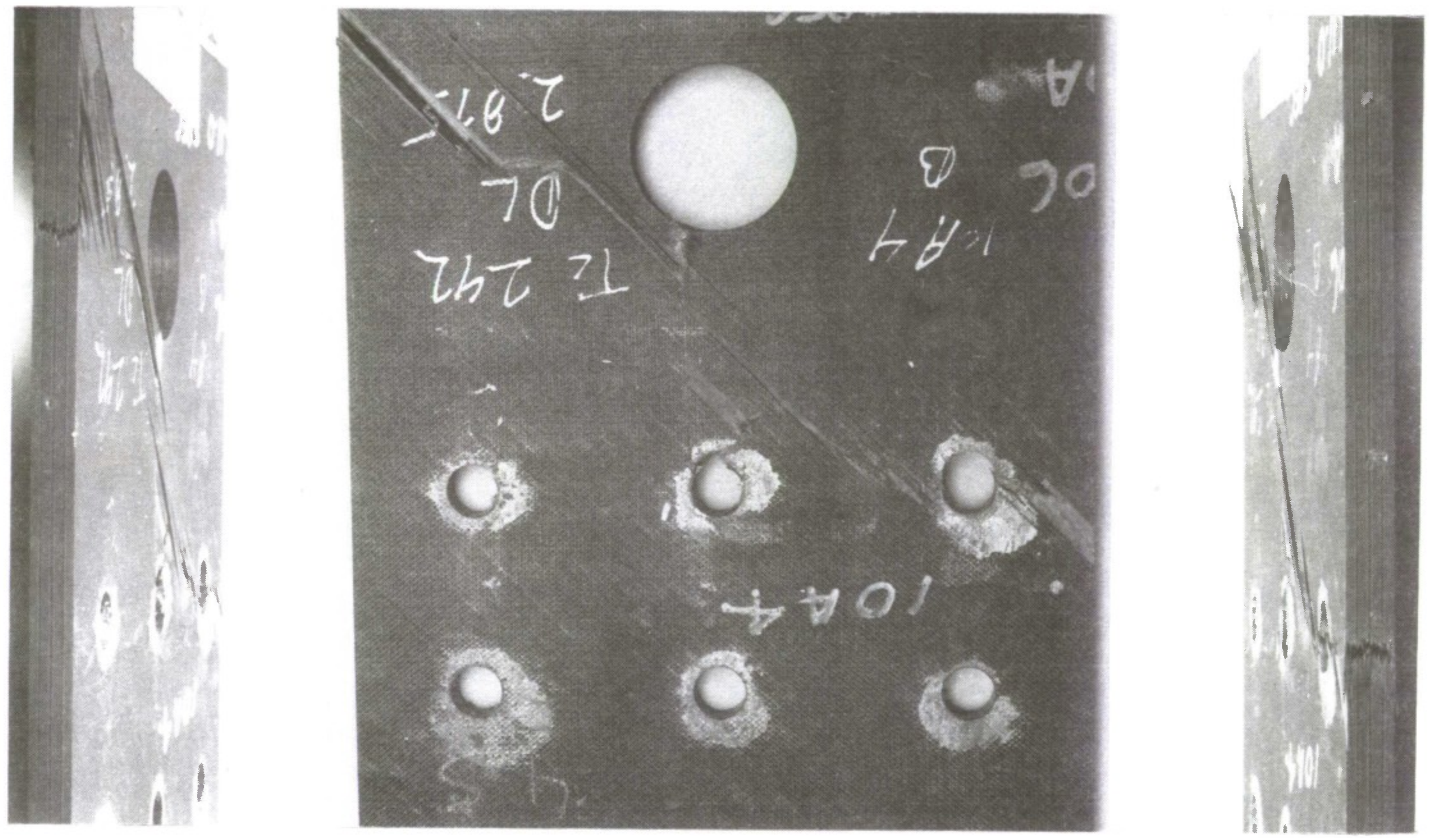
TEST CASE 242
SPECIMEN 10B10

TOTAL SURVEY LOAD	= 21000.0	POUNDS
THE SUM OF THE AXIAL LOADS ON ALL BOLTS	= 20729.1	POUNDS
THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS	= 270.9	POUNDS
DIFFERENCE PER BOLT	= 45.2	POUNDS



HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	D314	5.35	0.65	3944.8	-4.88
B	D310	3.64	-1.11	3949.1	5.78
C	D312	3.05	-0.24	2811.9	0.76
D	D39	4.11	-0.25	3743.4	-1.08
E	D38	2.11	-0.25	3307.5	-4.64
F	D315	3.80	0.52	3030.9	5.20

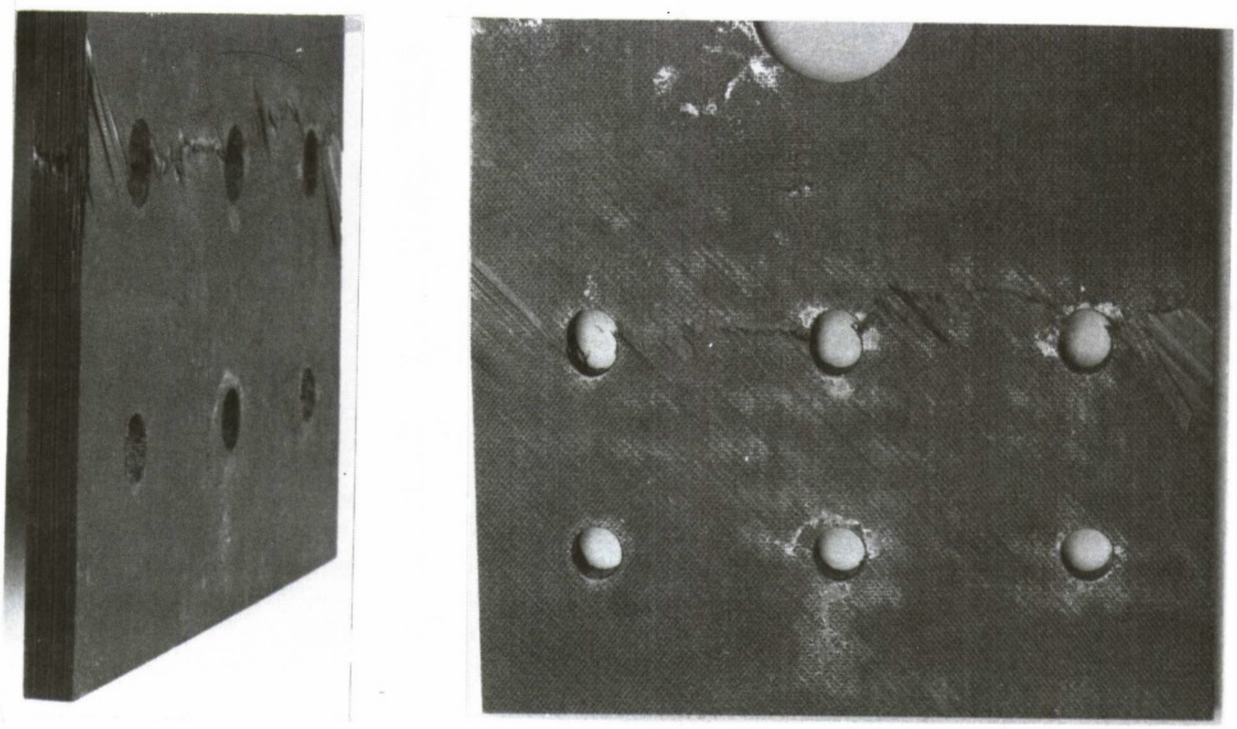
Figure 3-53. Fastener Load Measurements Using Strain-Gaged Bolts for Test Cases 240 to 242.



TC 242

SPEC 10A4

Figure 3-54. Failed Specimens from Test Case 242.



TC 242
SPEC 10B10

Figure 3-54. A Different Failure Mode Observed in Test Case 242. (Concluded).

cut-out or along the fastener row (see Figure 3-55). When the protruding head fasteners were replaced by 100° countersunk fasteners, partial shear-out was also observed (see Figure 3-56).

All the 40-Ply 70/20/10 laminates, subjected to tensile loading in a single shear configuration, suffered a partial shear-out failure, accompanied by delaminations that extended to specimen edges (see Figure 3-57). 40-ply, 25/60/15 laminates exhibited net section failures that were either across the circular cut-out or the nearest row of fasteners (see Figure 3-58).

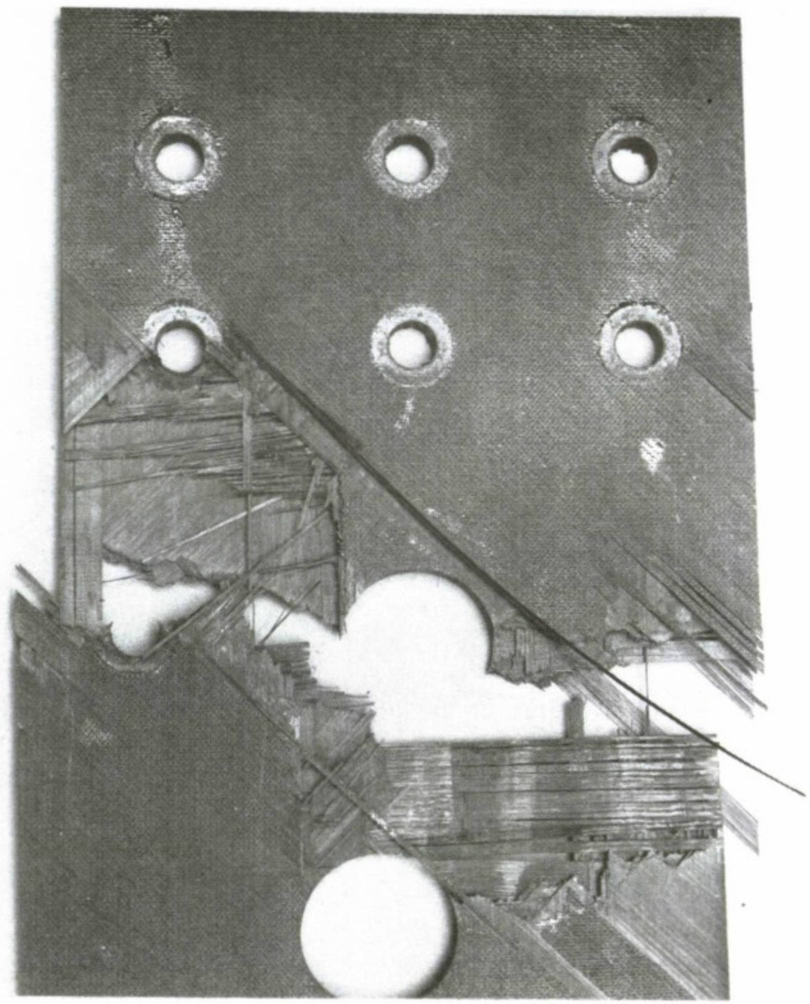
Test case 248 in Table 2-1 refers to joints with eight fasteners and a neighboring one inch diameter cut-out. In this case, the transverse fastener spacing was reduced to 4D. Figure 3-59 indicates that net section failures were introduced across the row of fasteners near the circular cut-out.

In test case 249 (Table 2-1), the circular cut-out was made less critical by placing it between the two rows of fasteners (four fasteners per row). In this case, failure was precipitated by a net section failure across a row of fasteners (see Figure 3-60).

The fractional fastener loads, corresponding to the applied survey loads, based on strain-gaged bolt measurements, are presented in Figures 3-53, 3-61 and 3-62, for test cases 242 to 249.

3.6 Results from Tests on Joints with Five Fasteners in Tandem

Test cases 250 to 253 in Table 2-1 considered five fasteners in tandem in the 40-ply 50/40/10 laminates and the metal plates. In every case, failure occured at the critical fastener location, in a net section mode (see Figure 3-63). The fractional fastener loads, corresponding to the survey load level, were computed based on strain-gaged bolt measurements (see Figurs 3-64 and 3-65). The use of countersunk fasteners resulted in lower failure loads (compare test cases 251 and 252 in Table 3-1).



TC 243
SPEC 10B11

TC 243
SPEC 10B15

Figure 3-55. Failed Specimens from Test Case 243.

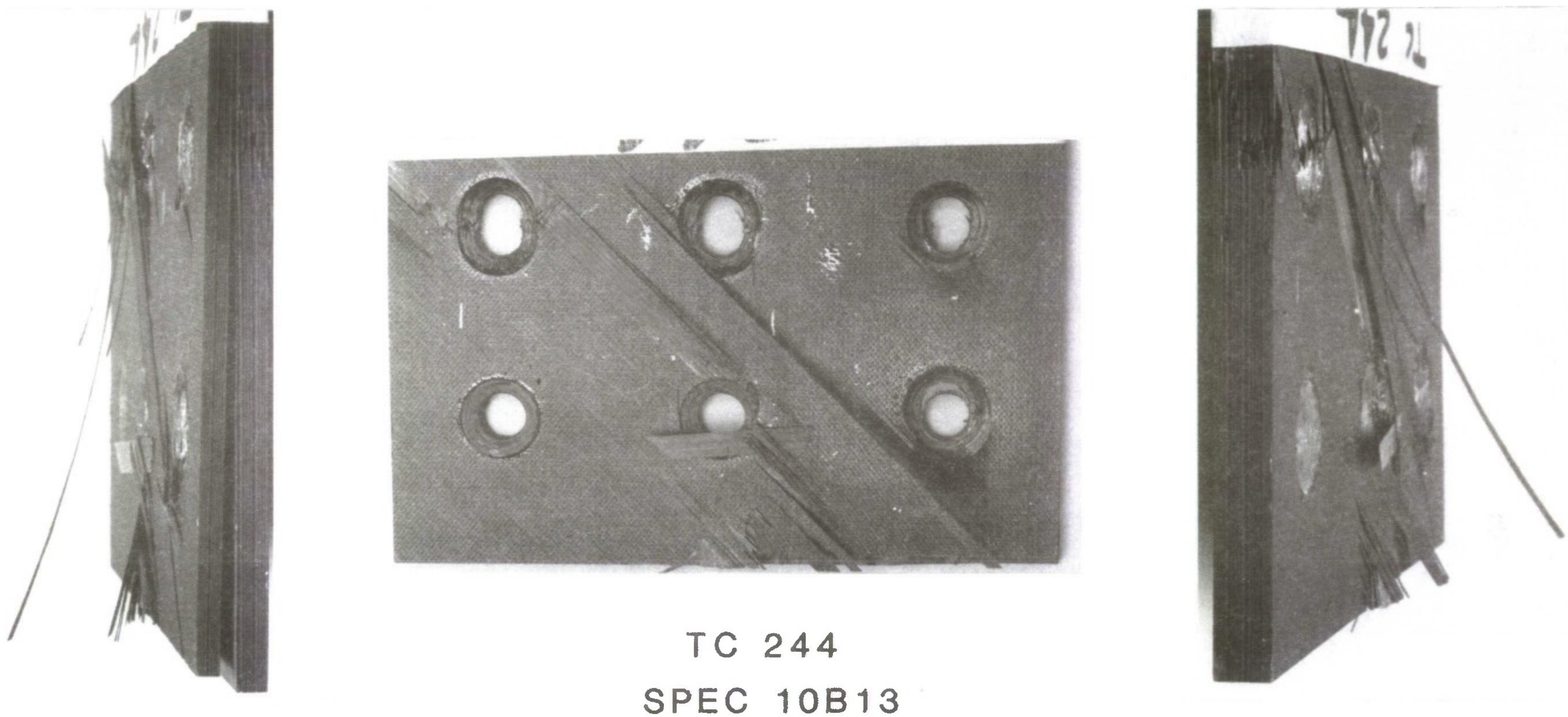


Figure 3-56. Failed Specimens from Test Case 244.

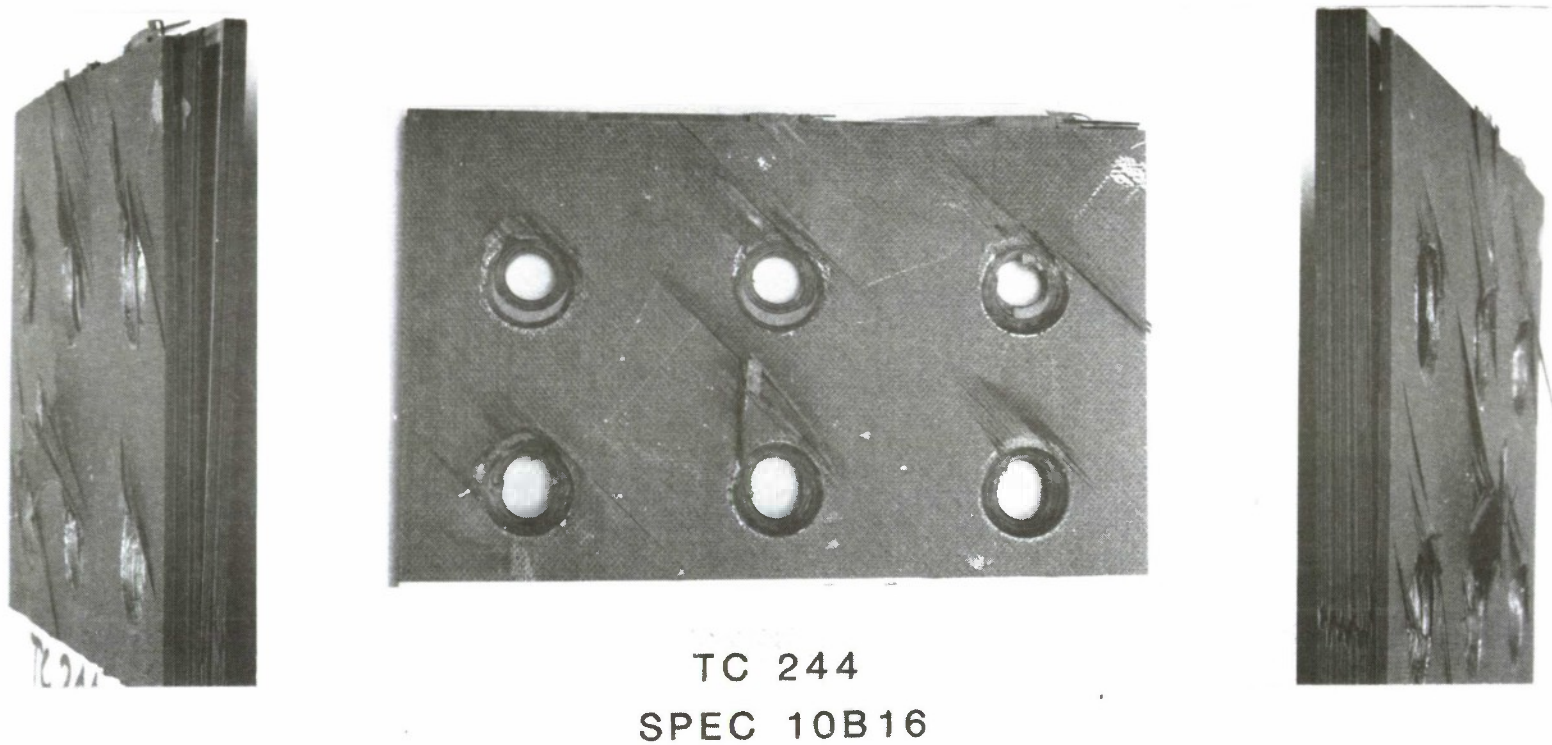
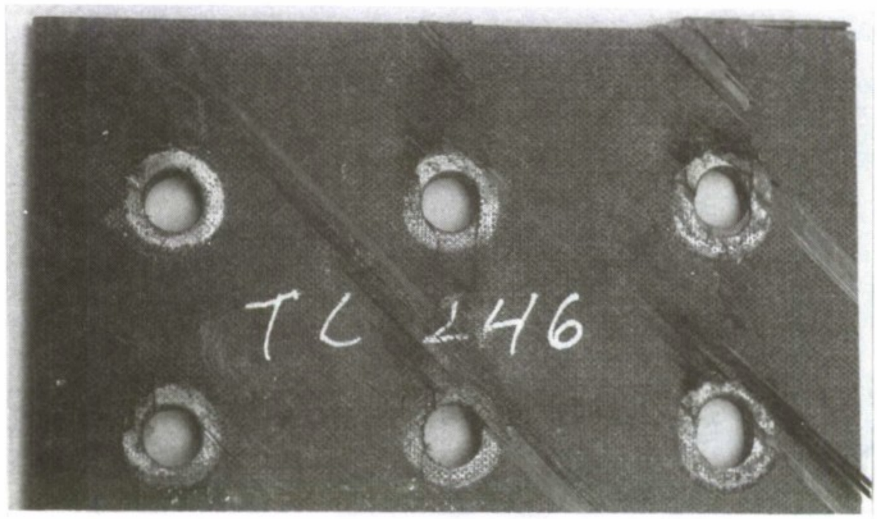
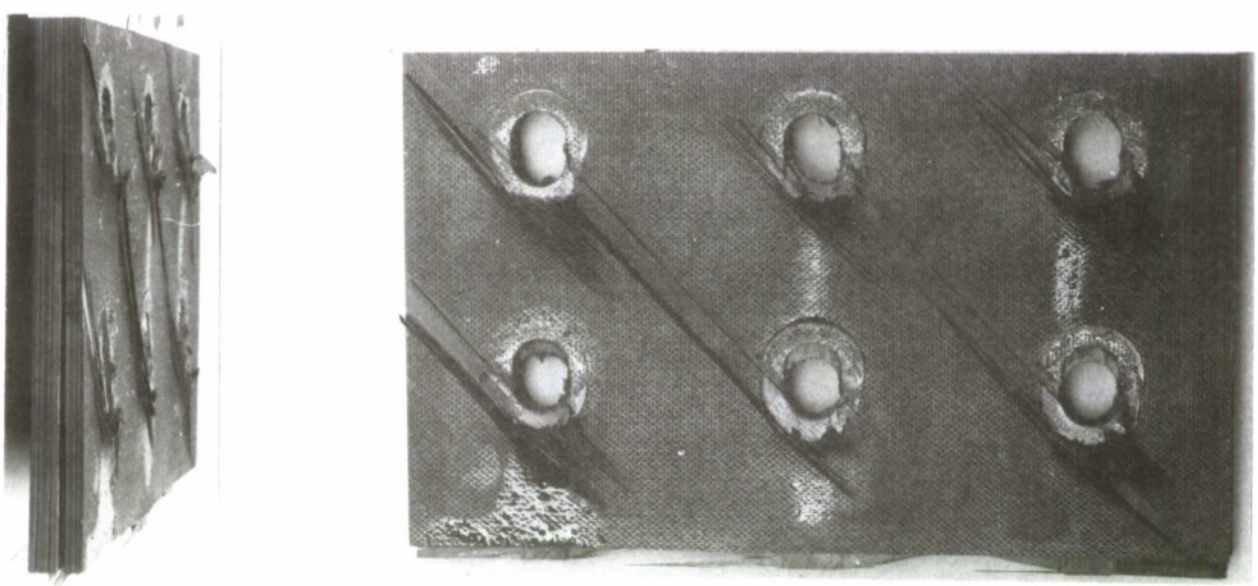


Figure 3-56. A Different Failure Mode Observed in Test Case 244. (Concluded).

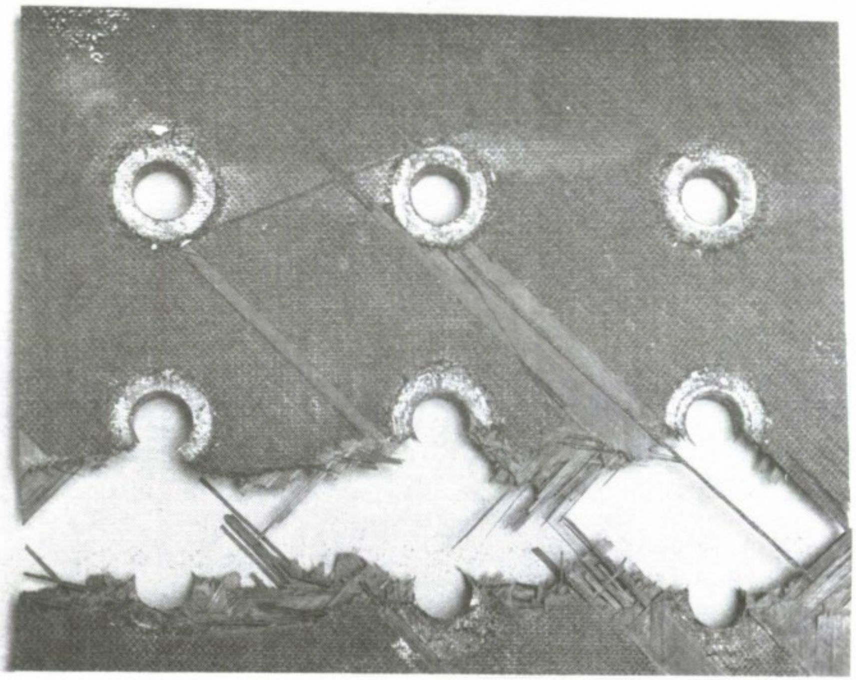


TC 246
SPEC 12.1

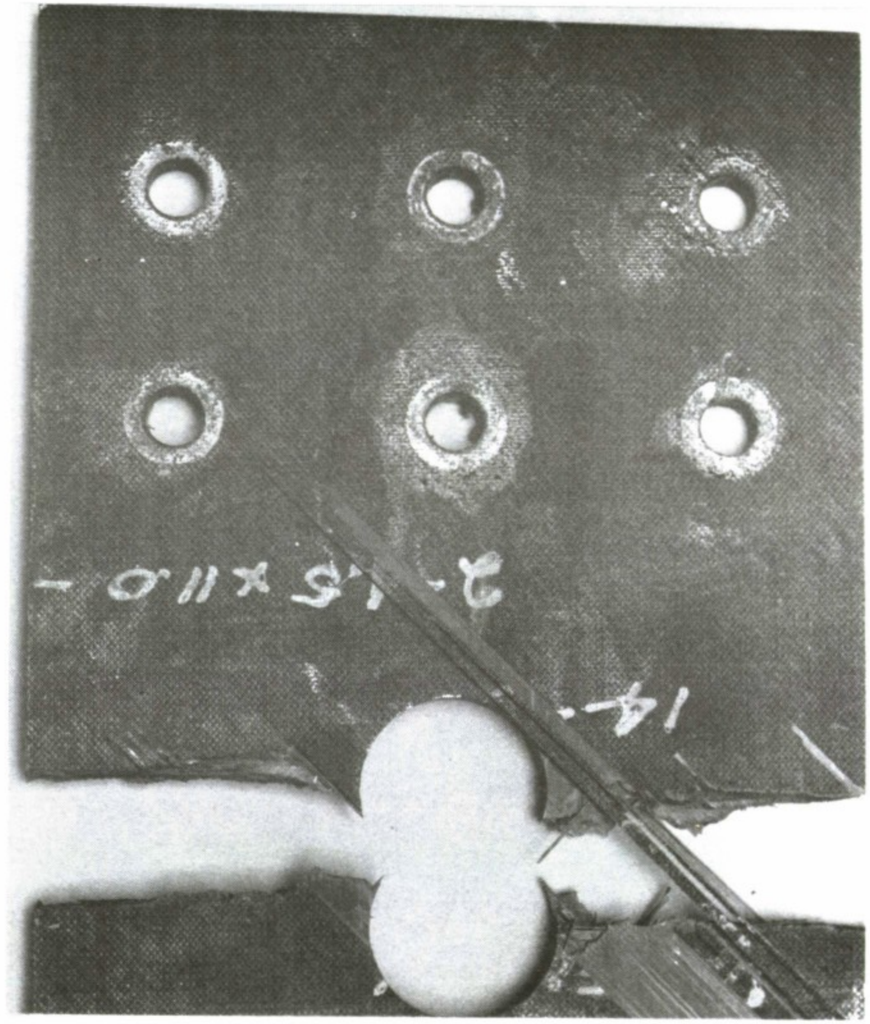


TC 246
SPEC 12.2

Figure 3-57. Failed Specimens from Test Case 246.

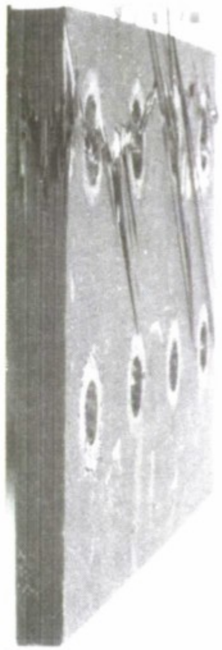


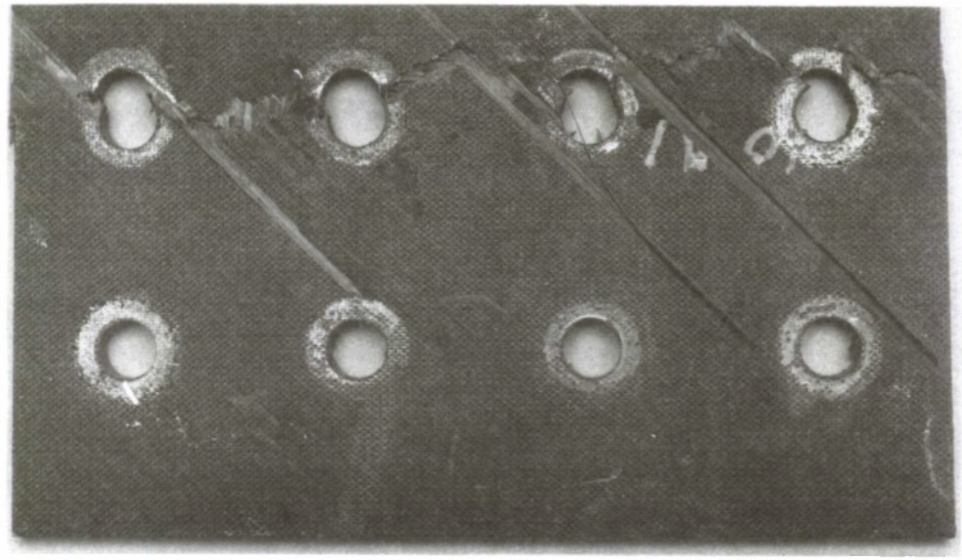
TC 247
SPEC 14.1



TC 247
SPEC 14.3

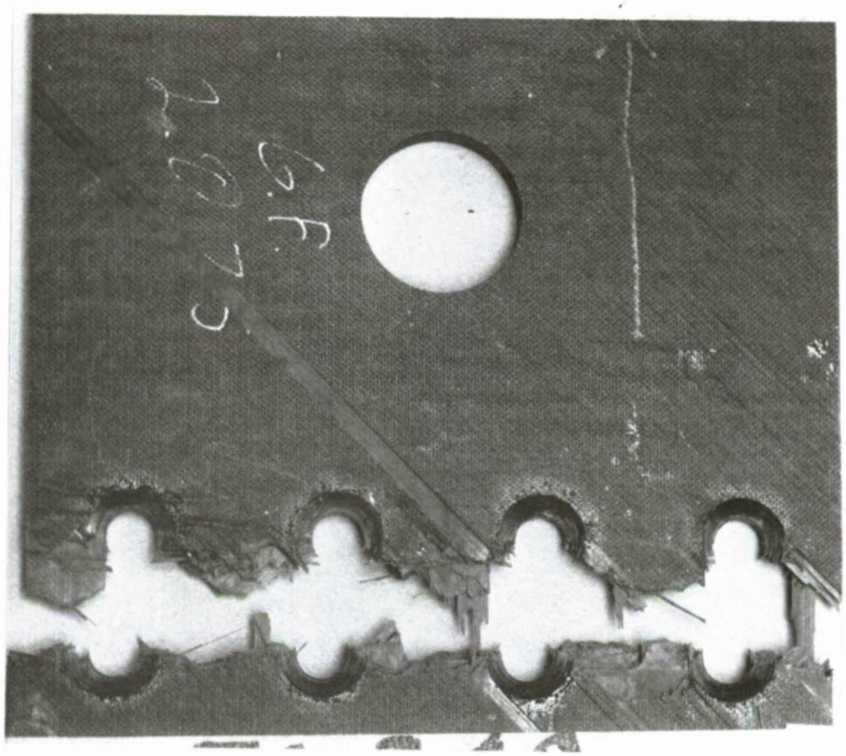
Figure 3-58. Failed Specimens from Test Case 247.





TC 248
SPEC 10A1

Figure 3-59. Failed Specimen from Test Case 248.

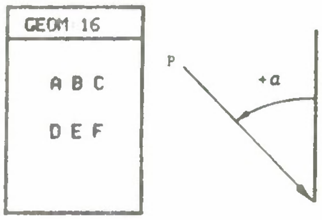


TC 249
SPEC 10A5

Figure 3-60. Failed Specimen from Test Case 249.

TEST CASE 243
SPECIMEN 10B15

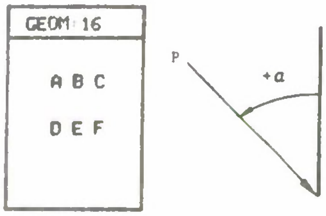
TOTAL SURVEY LOAD	= 12000.0	POUNDS
THE SUM OF THE AXIAL LOADS ON ALL BOLTS	= 11513.6	POUNDS
THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS	= 486.4	POUNDS
DIFFERENCE PER BOLT	= 81.1	POUNDS



HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	313	-3.73	0.92	2035.1	2.30
B	315	-4.15	0.04	1851.1	6.80
C	39	-3.73	1.29	1896.1	2.98
D	311	-4.07	1.02	1861.8	1.61
E	310	-3.57	0.85	1730.9	-1.14
F	312	-4.50	0.60	2158.9	-2.43

TEST CASE 244
SPECIMEN 10B14

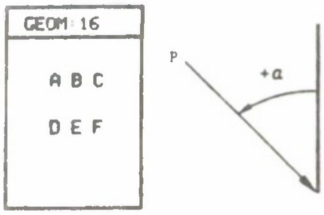
TOTAL SURVEY LOAD	= 12000.0	POUNDS
THE SUM OF THE AXIAL LOADS ON ALL BOLTS	= 12980.2	POUNDS
THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS	= -980.2	POUNDS
DIFFERENCE PER BOLT	= -163.4	POUNDS



HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	C311	-4.05	0.57	1881.5	-0.51
B	C310	-3.60	0.96	2031.9	-0.04
C	C312	-4.04	1.06	2154.6	1.04
D	C39	-4.10	1.08	2235.3	1.98
E	C315	-5.16	-0.70	2353.5	0.24
F	C313	-4.27	0.79	2325.3	0.31

TEST CASE 246
SPECIMEN 122

TOTAL SURVEY LOAD	= 12000.0	POUNDS
THE SUM OF THE AXIAL LOADS ON ALL BOLTS	= 11411.3	POUNDS
THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS	= 588.7	POUNDS
DIFFERENCE PER BOLT	= 98.1	POUNDS



HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	313	-3.66	0.80	1967.5	1.32
B	315	-4.68	-0.78	1897.1	-1.33
C	39	-2.84	1.27	1599.0	5.82
D	311	-3.81	1.14	1807.6	3.20
E	310	-3.59	1.38	1883.0	3.44
F	312	-4.80	0.61	2275.1	-2.66

Figure 3-61. Fastener Load Measurements Using Strain-Gaged Bolts for Test Cases 243 to 246.

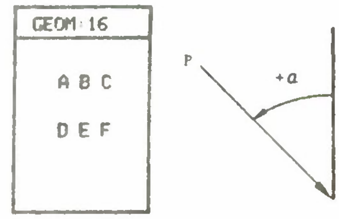
TEST CASE 247
SPECIMEN 142

TOTAL SURVEY LOAD = 12000.0 POUNDS

THE SUM OF THE AXIAL LOADS ON ALL BOLTS = 11619.6 POUNDS

THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS = 380.4 POUNDS

DIFFERENCE PER BOLT = 63.4 POUNDS



HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	313	-3.91	0.77	2052.9	0.54
B	315	-4.85	-0.60	1989.6	0.78
C	39	-3.23	1.57	1815.2	6.81
D	311	-3.99	1.14	1865.4	2.77
E	310	-3.67	0.99	1801.4	-0.08
F	312	-4.13	0.94	2110.6	0.88

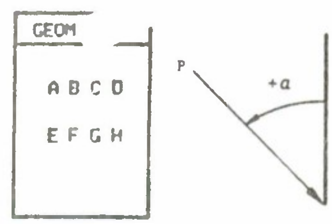
TEST CASE 248
SPECIMEN 10A3

TOTAL SURVEY LOAD = 16000.0 POUNDS

THE SUM OF THE AXIAL LOADS ON ALL BOLTS = 15387.1 POUNDS

THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS = 612.9 POUNDS

DIFFERENCE PER BOLT = 76.6 POUNDS



HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	313	-3.96	0.99	2146.6	2.41
B	315	-5.36	-1.05	2104.9	-2.81
C	39	-3.22	1.17	1693.9	3.50
D	311	-4.29	0.51	1819.6	-3.17
E	310	-3.77	1.25	1905.8	1.88
F	312	-4.28	1.36	2286.4	3.70
G	38	-2.03	0.63	1576.5	-2.44
H	314	-4.52	-0.10	1873.6	-3.05

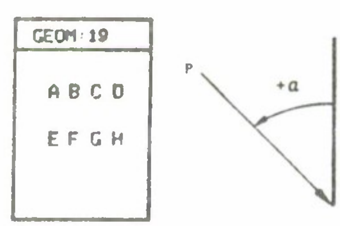
TEST CASE 249
SPECIMEN 10A6

TOTAL SURVEY LOAD = 16000.0 POUNDS

THE SUM OF THE AXIAL LOADS ON ALL BOLTS = 16440.5 POUNDS

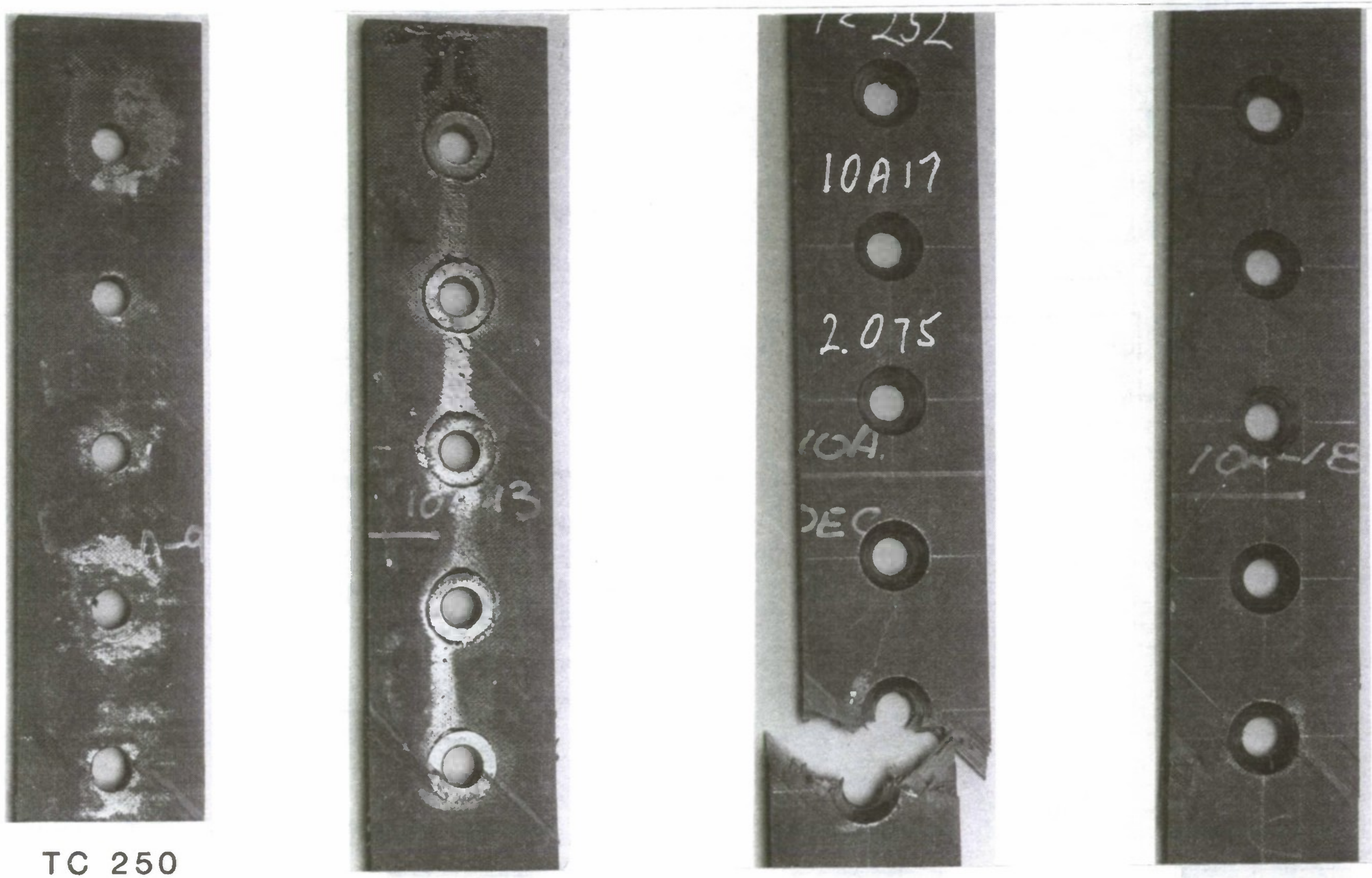
THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS = -440.5 POUNDS

DIFFERENCE PER BOLT = -55.1 POUNDS



HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	C313	-4.89	0.58	2499.3	-2.31
B	C315	-5.61	-1.27	2433.3	-4.54
C	C39	-4.11	0.09	1931.6	-7.52
D	C311	-3.23	0.25	1514.1	-3.01
E	C310	-4.25	0.10	2024.1	-9.61
F	C312	-3.70	1.60	2223.8	6.26
G	C38	-1.76	0.87	2074.6	5.27
H	C314	-3.54	0.63	1831.5	6.78

Figure 3-62. Fastener Load Measurements Using Strain-Gaged Bolts for Test Cases 247 to 249.



TC 250
SPEC 10A9

TC 251
SPEC 10A13

TC 252
SPEC 10A17

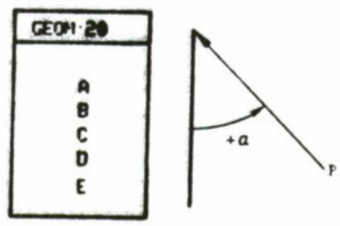
TC 253
SPEC 10A18

Figure 3-63. Failed Specimens from Test Cases 250 to 253.

READY

TEST CASE 250
SPECIMEN 10B6

TOTAL SURVEY LOAD	= 10000.0	POUNDS
THE SUM OF THE AXIAL LOADS ON ALL BOLTS	= 11150.2	POUNDS
THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS	= -1150.2	POUNDS
DIFFERENCE PER BOLT	= -230.0	POUNDS

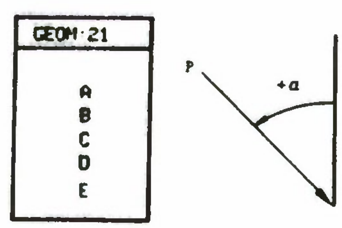


HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	D310	3.89	-0.48	3843.6	0.05
B	D312	2.33	-0.29	2305.6	2.05
C	D314	1.82	-0.04	1797.1	1.61
D	D315	1.33	0.30	1386.1	0.83
E	D39	1.50	-0.35	1826.5	4.74

READY

TEST CASE 251
SPECIMEN 10A13

TOTAL SURVEY LOAD	= 10000.0	POUNDS
THE SUM OF THE AXIAL LOADS ON ALL BOLTS	= 9825.7	POUNDS
THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS	= 174.3	POUNDS
DIFFERENCE PER BOLT	= 34.9	POUNDS



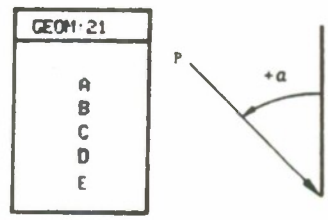
HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	313	-4.85	1.47	2651.9	4.15
B	315	-4.12	-0.42	1751.0	1.82
C	39	-3.44	0.87	1684.7	0.05
D	311	-4.04	0.54	1743.5	-2.60
E	310	-4.41	0.81	2007.1	-3.06

Figure 3-64. Fastener Load Measurements Using Strain-Gaged Bolts for Test Cases 250 and 251.

READY

TEST CASE 252
SPECIMEN 10A14

TOTAL SURVEY LOAD	= 10000.0	POUNDS
THE SUM OF THE AXIAL LOADS ON ALL BOLTS	= 10472.0	POUNDS
THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS	= -472.0	POUNDS
DIFFERENCE PER BOLT	= -94.4	POUNDS

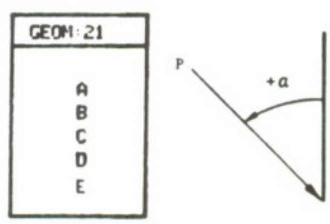


HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	C313	-4.40	1.52	2664.7	5.65
B	C315	-4.70	-0.48	2204.8	1.90
C	C39	-3.09	0.83	1764.1	2.15
D	C311	-3.53	0.73	1736.8	1.93
E	C310	-3.91	0.86	2118.9	-1.66

READY

TEST CASE 253
SPECIMEN 10A15

TOTAL SURVEY LOAD	= 10000.0	POUNDS
THE SUM OF THE AXIAL LOADS ON ALL BOLTS	= 5571.2	POUNDS
THE DIFFERENCE BETWEEN THE BOLT SURVEY LOAD AND THE SUM OF THE AXIAL LOADS	= 4428.8	POUNDS
DIFFERENCE PER BOLT	= 885.8	POUNDS



HOLE	BOLT ID	230 DEG. (VOLTS)	280 DEG. (VOLTS)	LOAD ON BOLT (POUNDS)	ANGLE (DEGREES)
A	C313	-2.51	1.04	1719.9	7.57
B	C315	-1.89	0.0	1112.6	6.61
C	C39	-0.66	0.41	698.8	11.39
D	C311	-0.93	0.28	702.3	5.10
E	C310	-2.35	0.47	1377.7	-2.38

Figure 3-65. Fastener Load Measurements Using Strain-Gaged Bolts for Test Cases 252 and 253.

SECTION 4

CONCLUSIONS

An extensive test program was conducted to study the effect of many parameters on composite-to-metal multifastener joints. The addressed parameters included: laminate layup, fastener arrangement, adjacent cut-out, load type, load eccentricity (single versus double shear), fastener head geometry, and test environment. Test laminates were fabricated using unidirectional AS1/3501-6 graphite/epoxy material, and transferred the applied load to aluminum plates.

Test results were obtained on many fastener arrangements, including some with a neighboring circular cut-out. Many failure modes were observed and recorded. In some test cases, despite the close tolerances in the specimen/hole/fastener geometries, different predominant failure modes were observed in the replicates. Generated test results are complementary to available results on AS1/3501-6 graphite/epoxy bolted laminates (References 4-1 to 4-6).

A unique fastener load measurement technique, developed in Reference 4.7, was applied to every test case to compute the fractional fastener loads corresponding to the various test conditions. This information, in conjunction with photographic records of failed test specimens, will be very useful in validating the strength analysis of multifastener joints developed in the ongoing Northrop/AFWAL program.

Presented test results will be further analyzed and summarized in the design guide that is being developed in this ongoing Northrop/AFWAL program. Existing guidelines will be reiterated, further qualified or modified, as necessary, and new guidelines will be developed, to facilitate the design of bolted composite structures.

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SUBJECT: Request for Public Release Approval (AFR/ASDR 190-1)

TO: WRDC/~~IST~~ ey 10/22/90
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IN TURN

1. Please review the attached material for public release approval. The following information is provided in support of this request:

a. Type of information (abstract, journal article, technical paper, film/script, technical report, etc): AFWAL-TR-85-3065 (AD#B099065L)

b. Title: Bolted Joints in Composite Structures: Design, Analysis and Verification Task II Test Results--Multifastener Joints

c. Author(s) name, title, and organization: R.L. Ramkumar and E. Tossavainen, Northrop Corporation, Aicraft Division

d. Contract #/company name: F33615-82-C-3217, Northrop Corporation

e. Name/location of publisher: N/A

f. To be presented at (give sponsoring organization or technical society, location (city, state), and exact date of presentation): N/A

g. Deadline for submittal (if other than presentation date): N/A

2. The reverse side of this letter has been completed/signed by requester.

3. The information contained in this material is unclassified, technically accurate, nonproprietary, and considered suitable for public release. It contains no computer software, owned or developed by or for the government. Export restrictions (ie, MCTL, Munitions List (ITAR), and CCL) and current AF/DOD policy have been considered prior to requesting public release approval.

FOR THE COMMANDER

SIGNED

(Division level/signature/title
ROBERT M. BADER
Chief, Structures Division

Higher echelon signature (if applicable)

ASD/PA APPROVAL

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